Functional MRI: Basics and Beyond

Peter A. Bandettini, Ph.D.

Section on Functional Imaging Methods

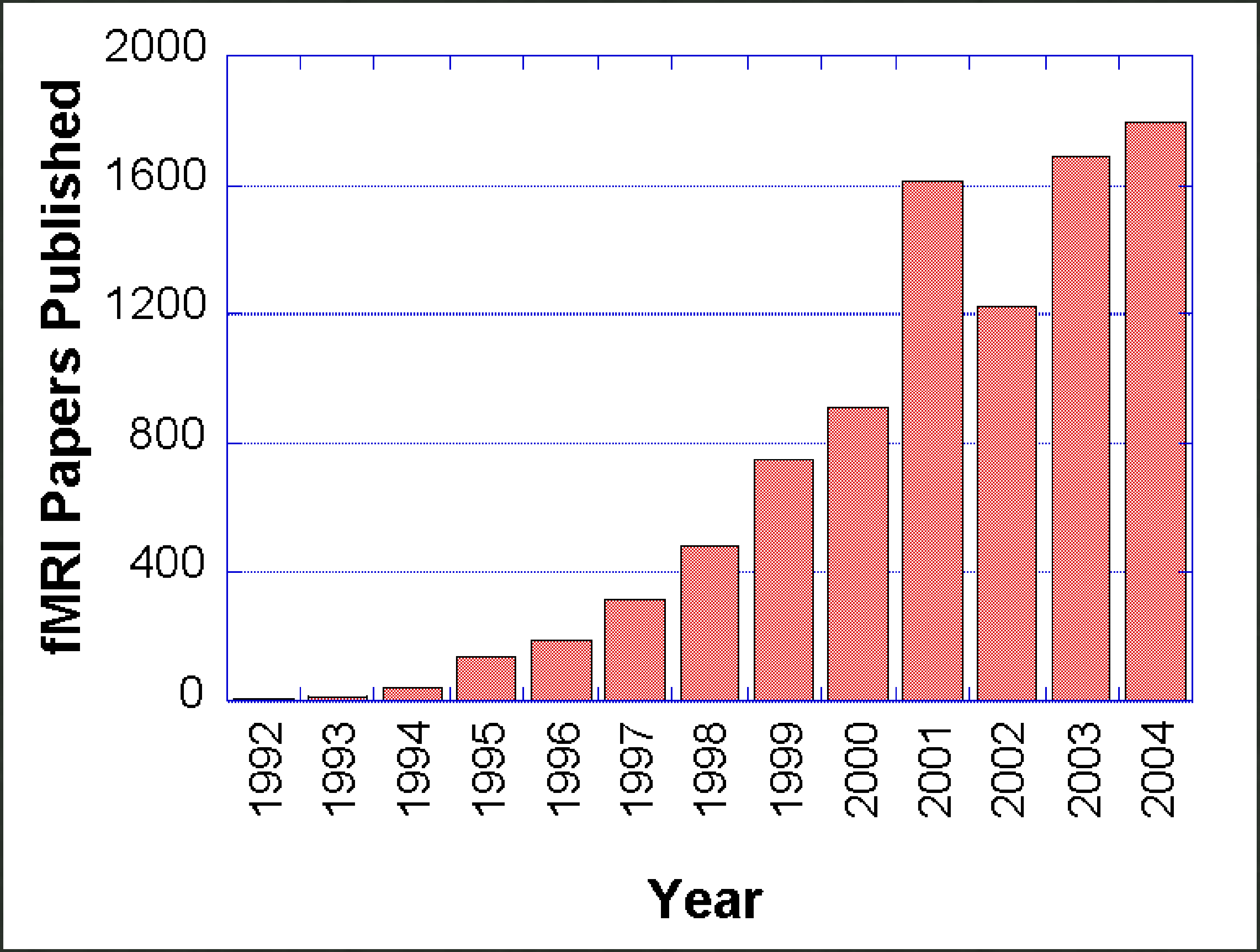
http://fim.nimh.nih.gov

Laboratory of Brain and Cognition

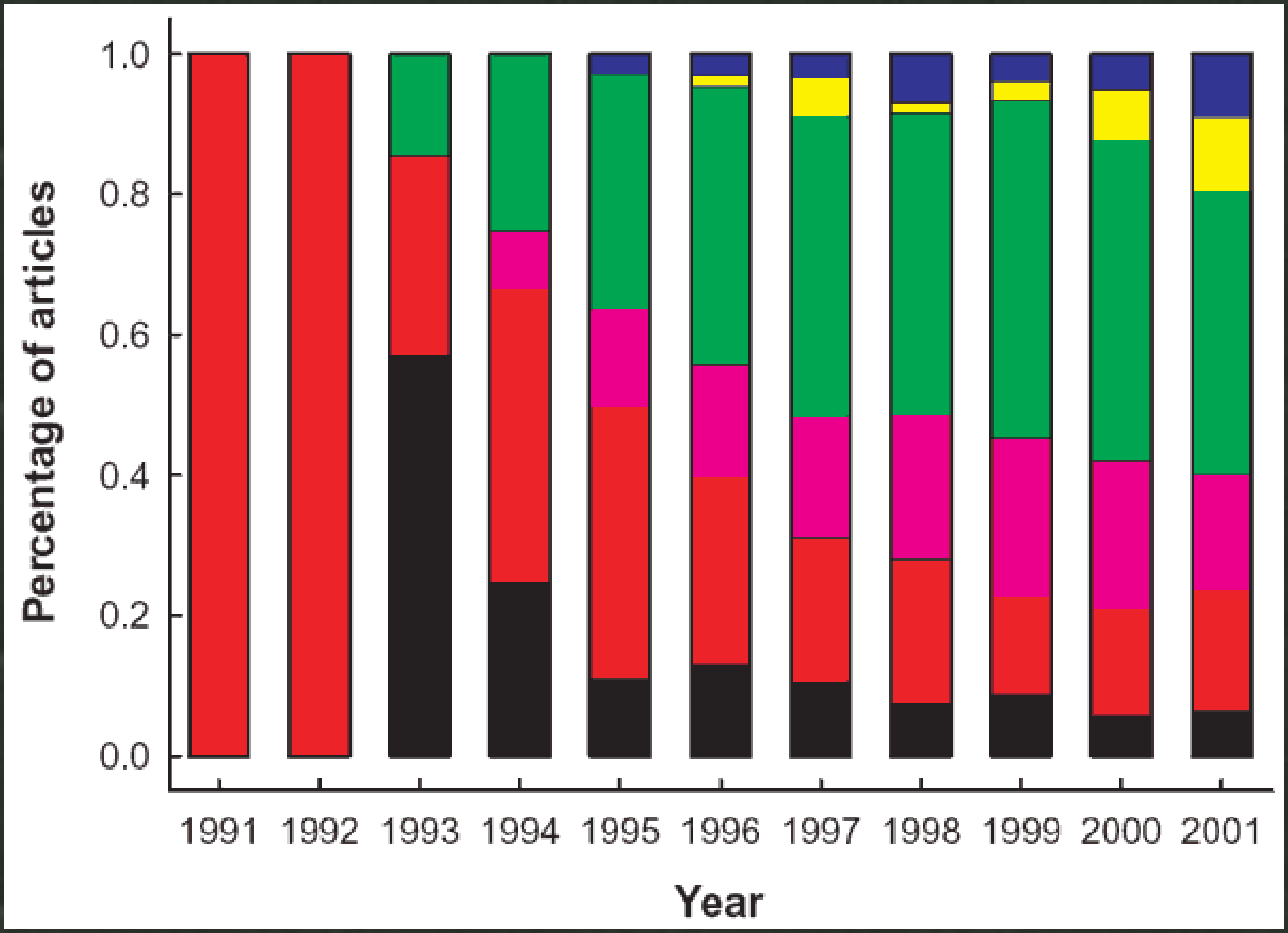
&

Functional MRI Facility

http://fnif.nimh.nih.gov

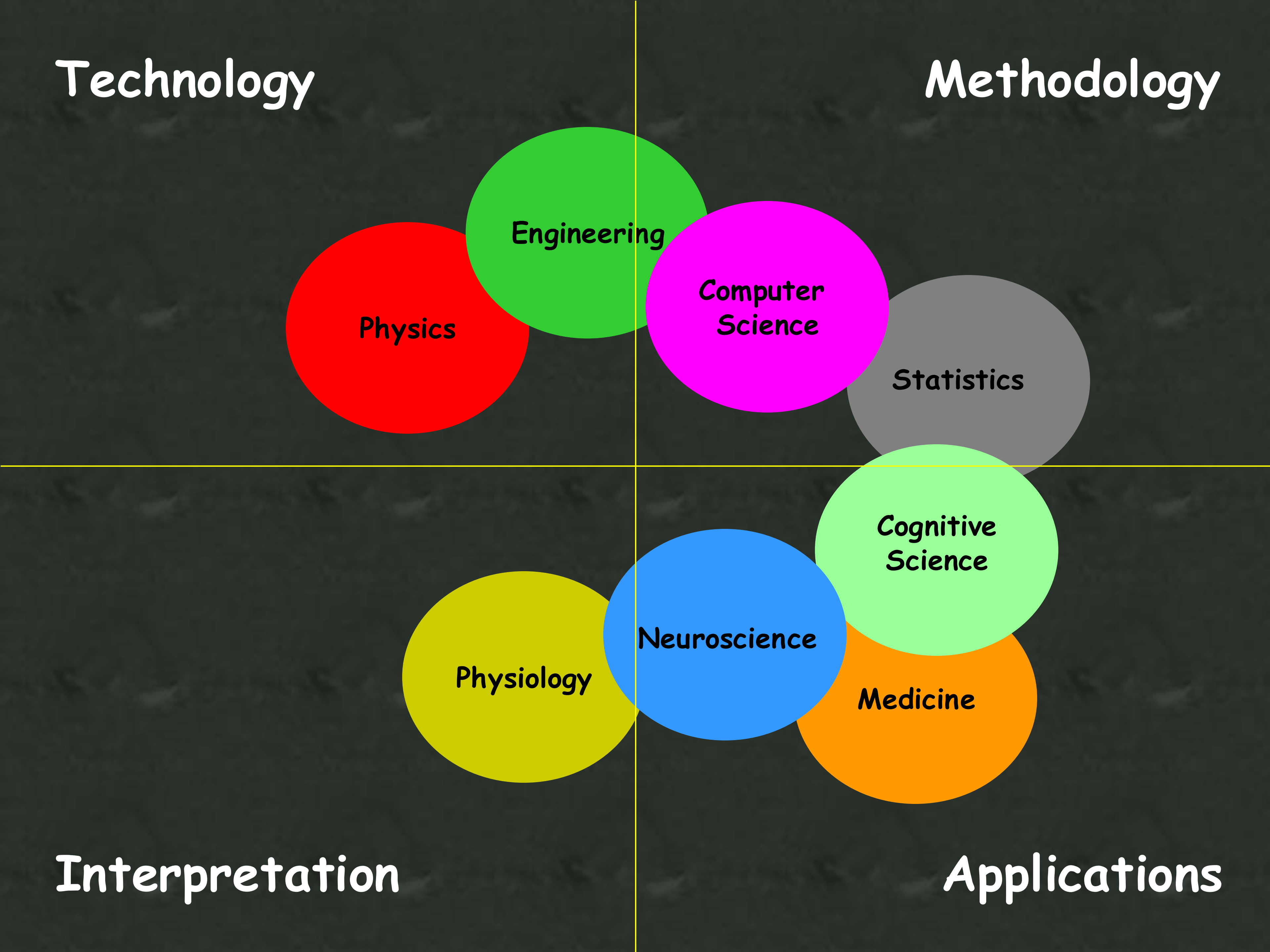


"fMRI" or "functional MRI"



Motor (black)
Primary Sensory (red)
Integrative Sensory (violet)
Basic Cognition (green)
High-Order Cognition (yellow)
Emotion (blue)

J. Illes, M. P. Kirschen, J. D. E. Gabrielli,
Nature Neuroscience, 6 (3)m p.205


Technology
Methodology
Engineering
Physics
Computer Science
Statistics
Cognitive Science
Neuroscience
Physiology
Medicine
Interpretation
Applications

fMRI Contrast

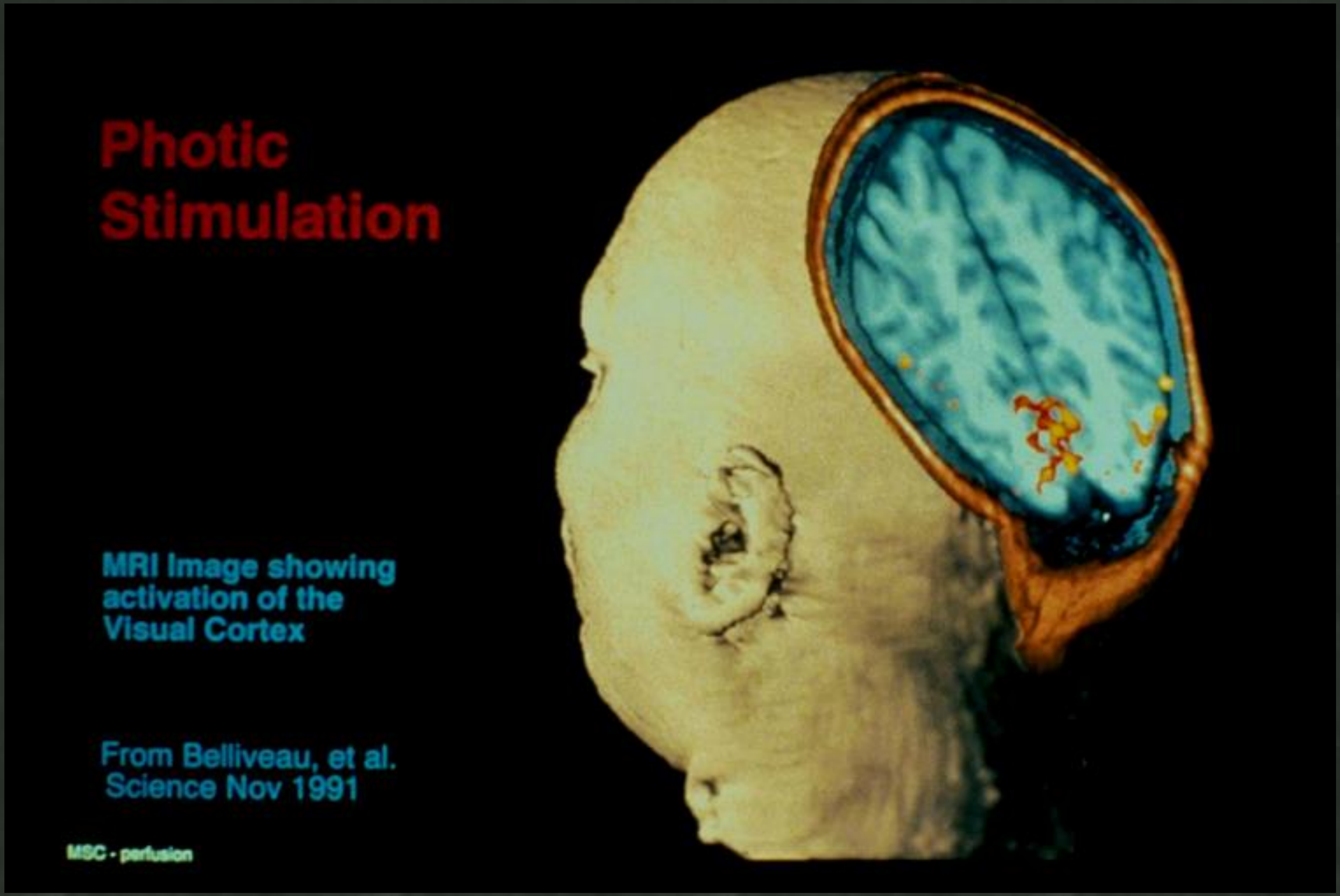
Blood Volume
Blood Oxygenation
Perfusion
New Contrasts
The HRF: Spatial and Temporal Resolution
The HRF: Interpretation

fMRI Methodology

Paradigm Design
Sensitivity and Noise

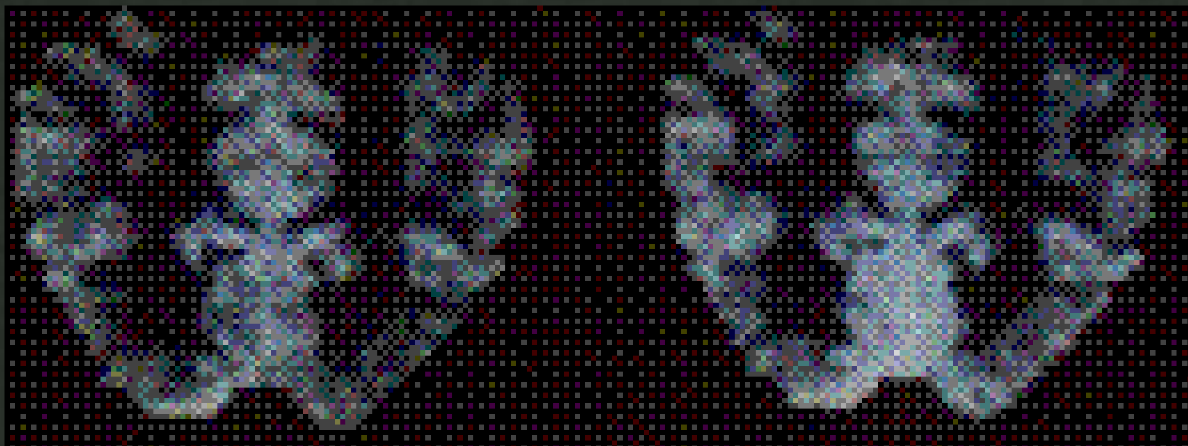
Blood Volume

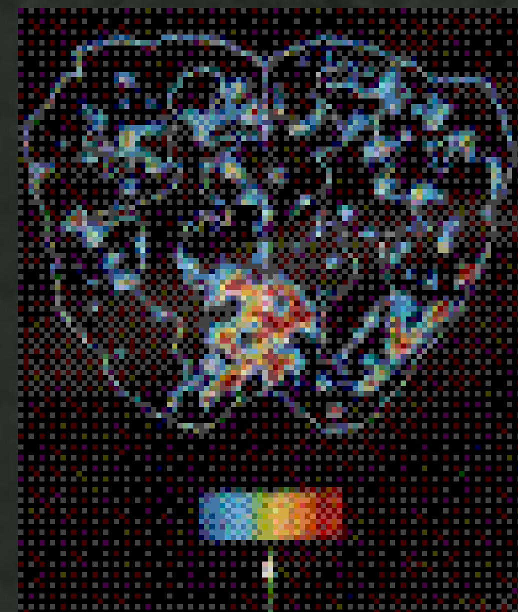
What started it all…



Blood Volume

Resting Active

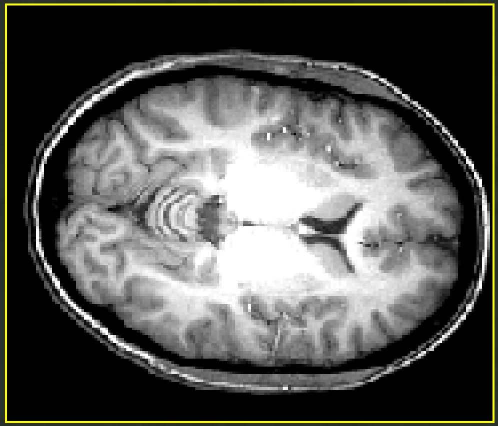




MRI vs. fMRI

MRI

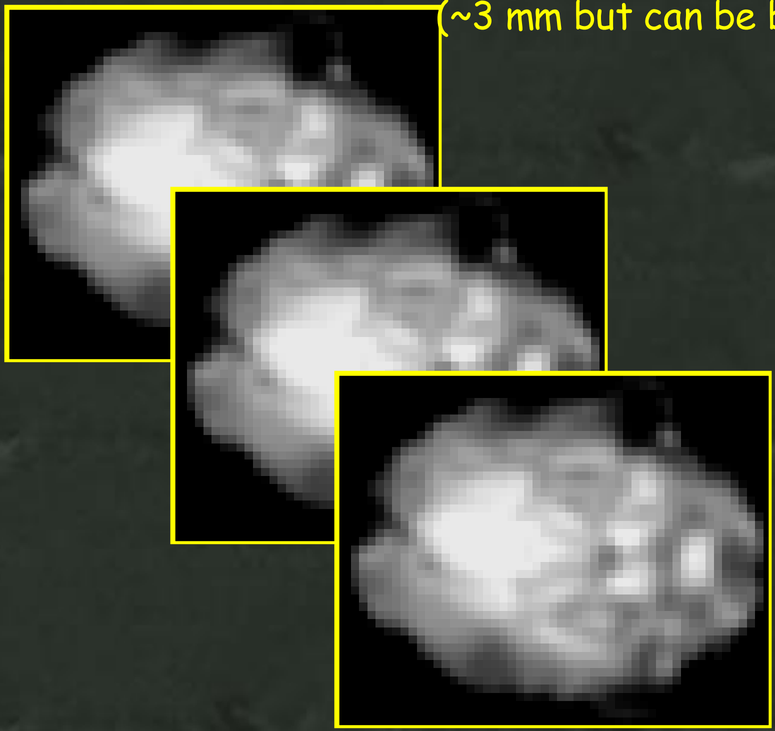
high resolution
(1 mm)



one image

fMRI

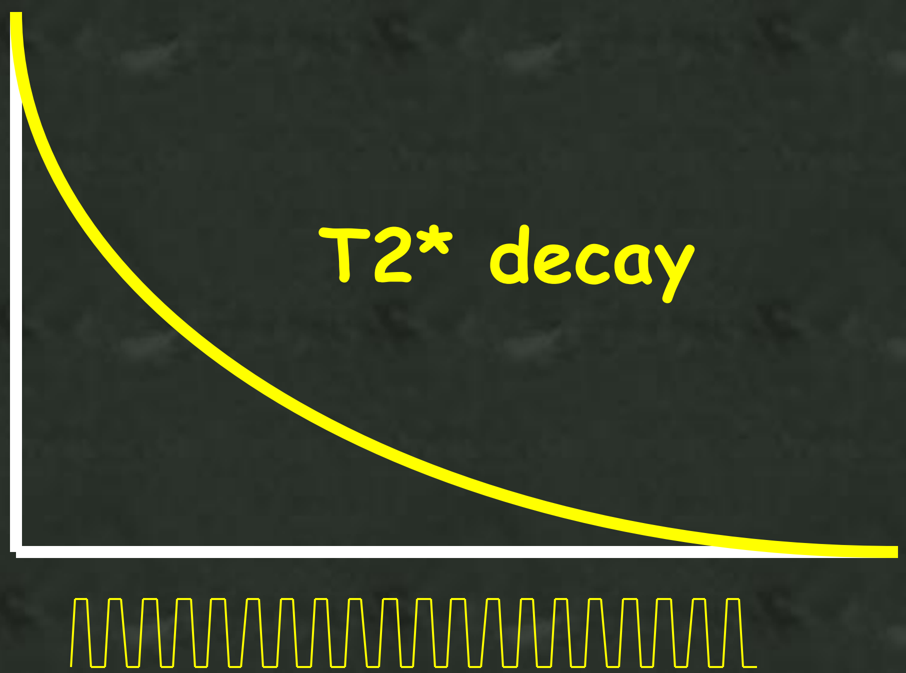
low resolution
(~3 mm but can be better)



...

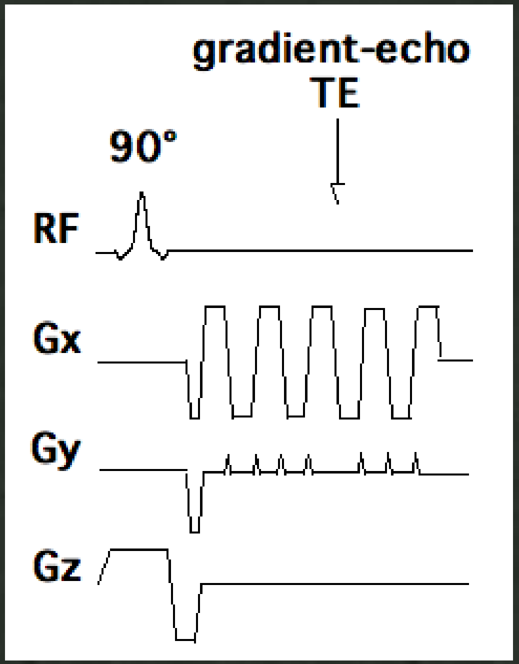
many images
(e.g., every 2 sec for 5 mins)

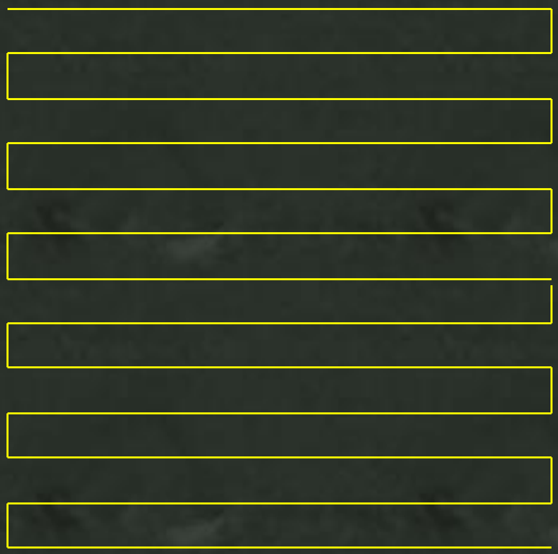
Single Shot Echo Planar Imaging (EPI)



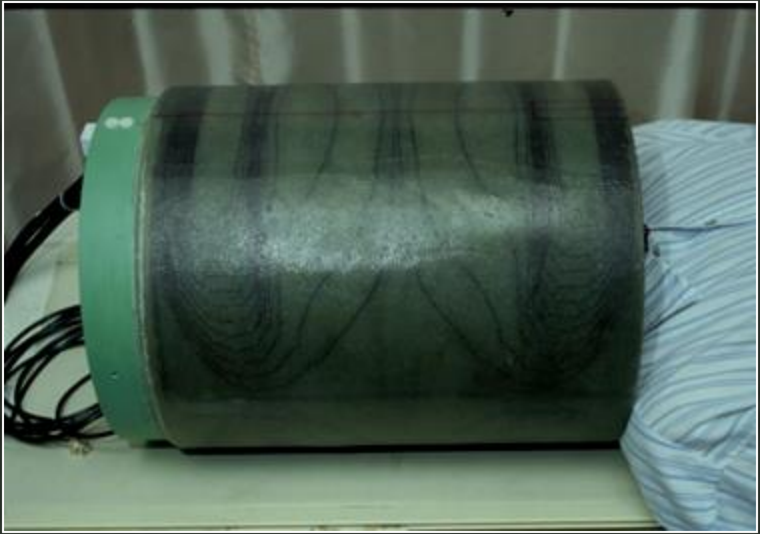
EPI Readout Window

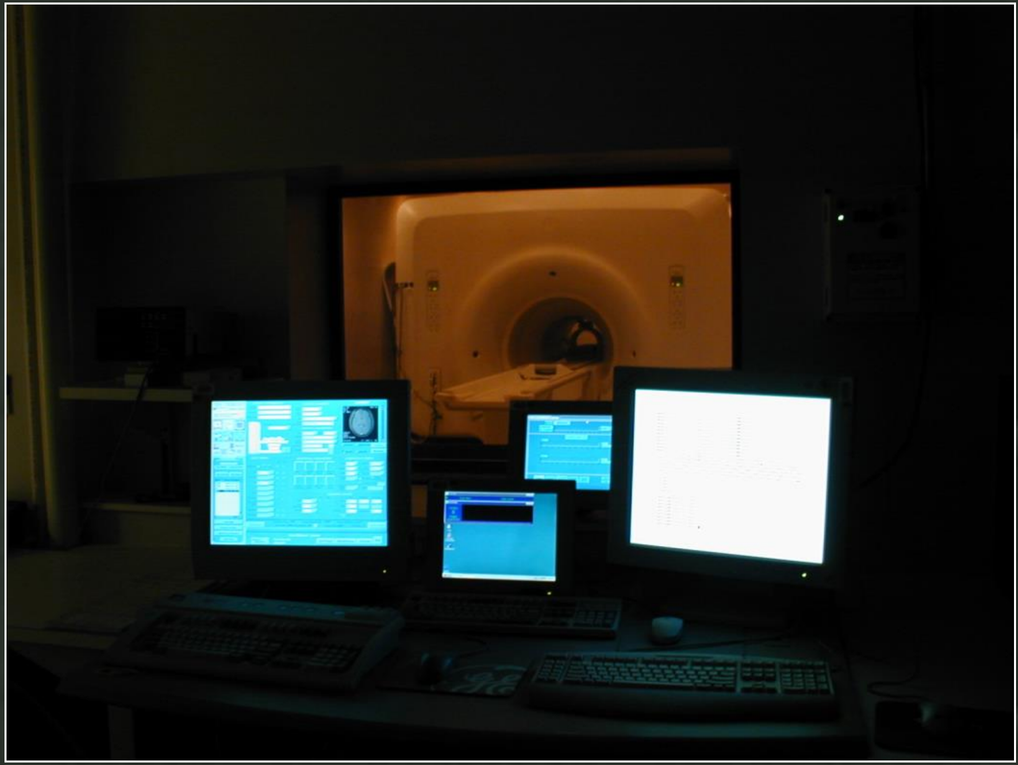
≈ 20 to 40 ms





Local Gradient Coil
(low inductance)





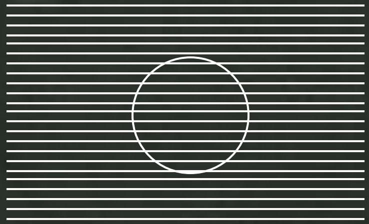
Whole body gradients
(more powerful amplifiers)

Blood Oxygenation

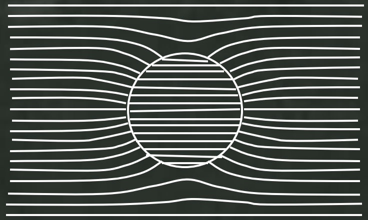
Oxygenated and deoxygenated red blood cells have different magnetic properties

red blood cells

oxygenated



deoxygenated



L. Pauling, C. D. Coryell, *Proc.Natl. Acad. Sci. USA 22, 210-216*, **1936**.

K.R. Thulborn, J. C. Waterton, et al., *Biochim. Biophys. Acta. 714: 265-270*, **1982**.

S. Ogawa, T. M. Lee, A. R. Kay, D. W. Tank, *Proc. Natl. Acad. Sci. USA 87, 9868-9872*, **1990**.

Blood Oxygenation

Cerebral Tissue Activation

↓

Local Vasodilatation

↓

Increase in Cerebral Blood Flow and Volume → Oxygen Delivery Exceeds Metabolic Need

↓

Increase in Capillary and Venous Blood Oxygenation

↓

Decrease in Deoxy-hemoglobin

Deoxy-hemoglobin: paramagnetic
Oxy-hemoglobin: diamagnetic

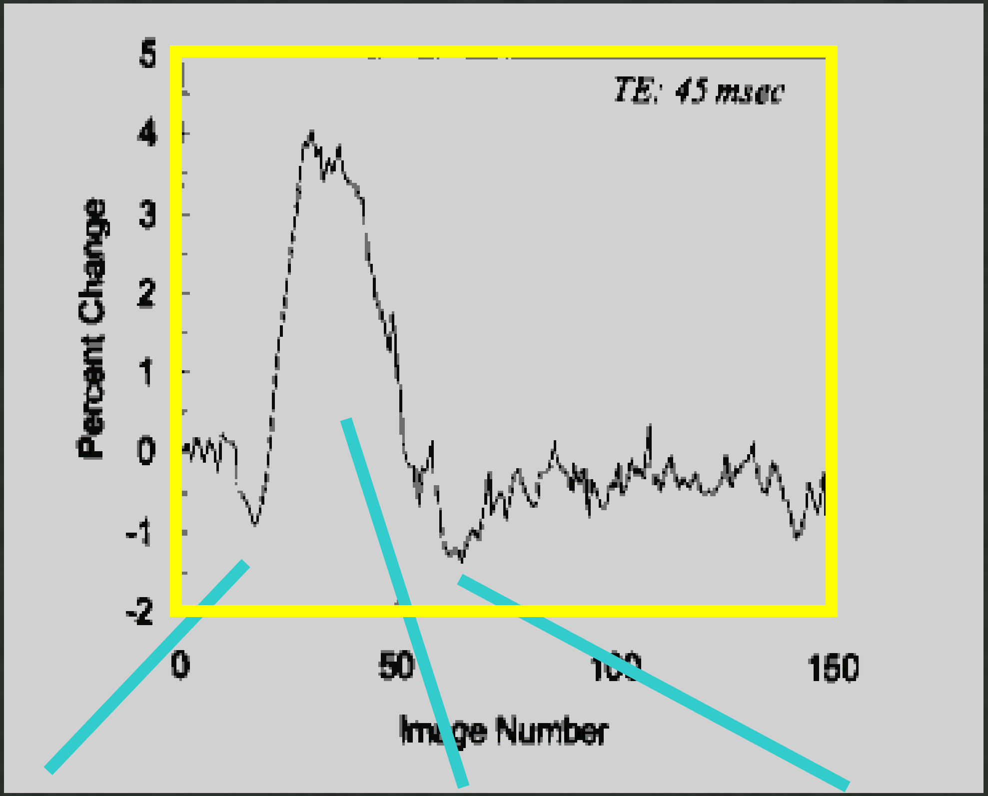
↓

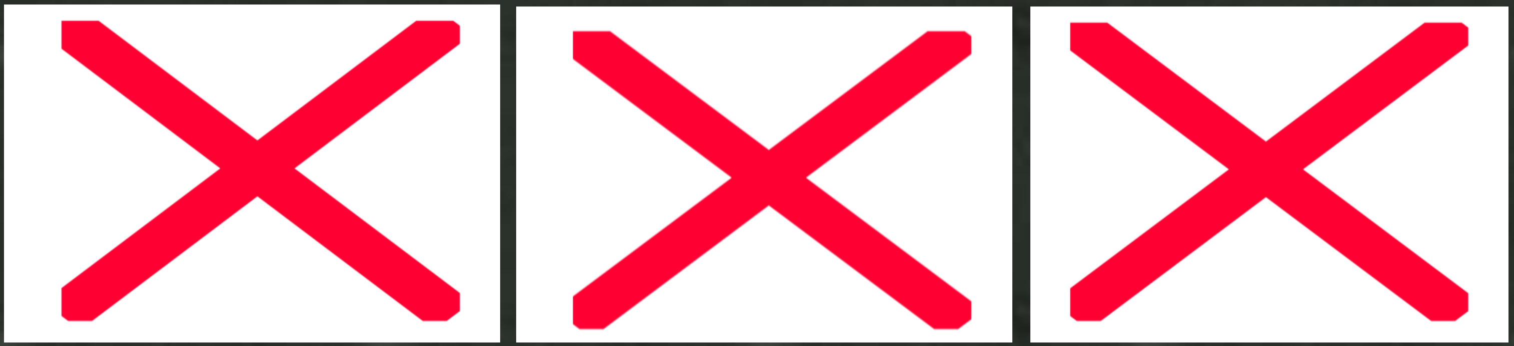
Decrease in susceptibility-related intravoxel dephasing → Increase in T2 and T2*

↓

Local Signal Increase in T2 and T2* - weighted sequences

Blood Oxygenation

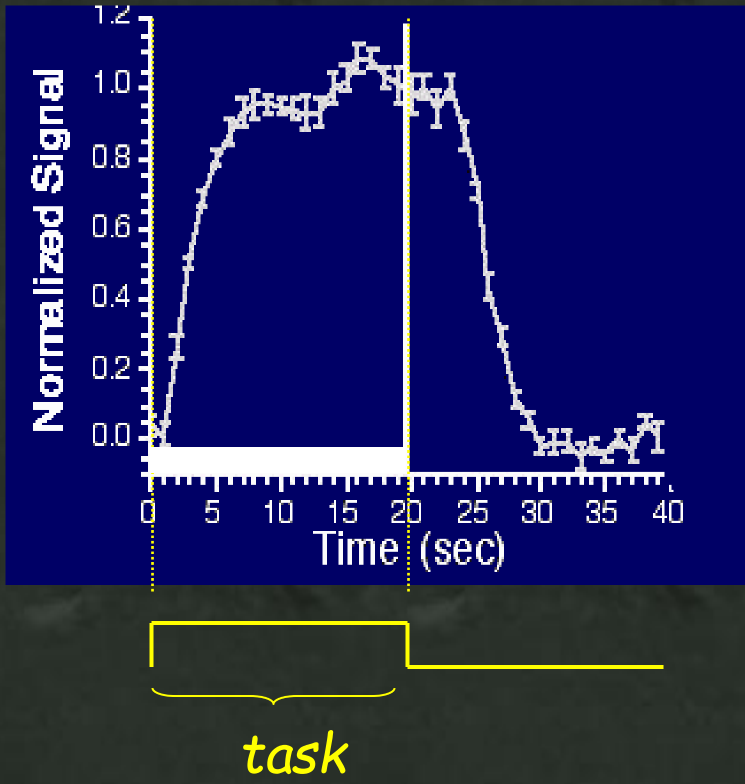


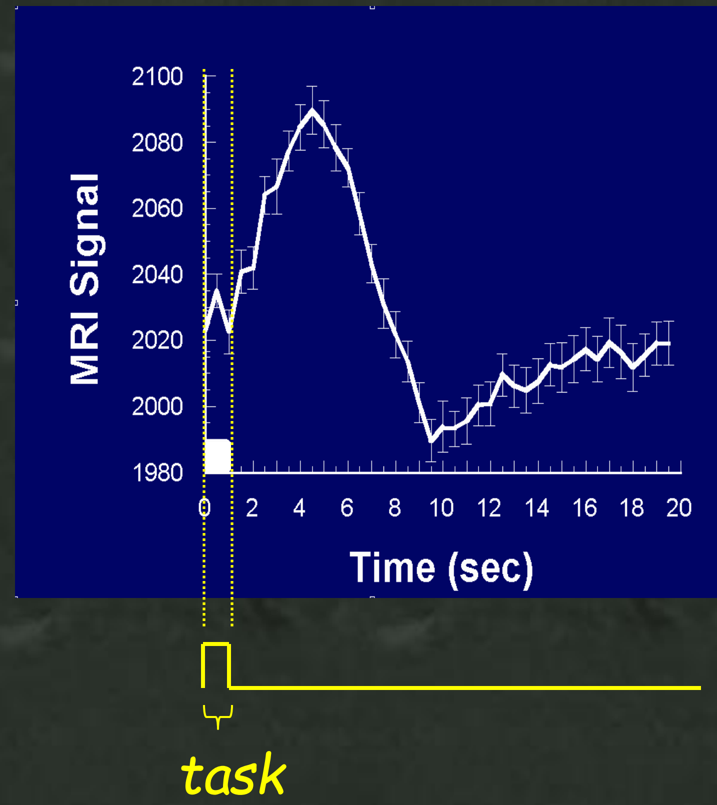


Yacoub E, Le TH, Ugurbil K, Hu X (1999) Magn Res Med 41(3):436-41

Courtesy of Arno Villringer

Blood Oxygenation





•K. K. Kwong, et al, (1992) "Dynamic magnetic resonance imaging of human brain activity during primary sensory stimulation." Proc. Natl. Acad. Sci. USA. 89, 5675-5679.

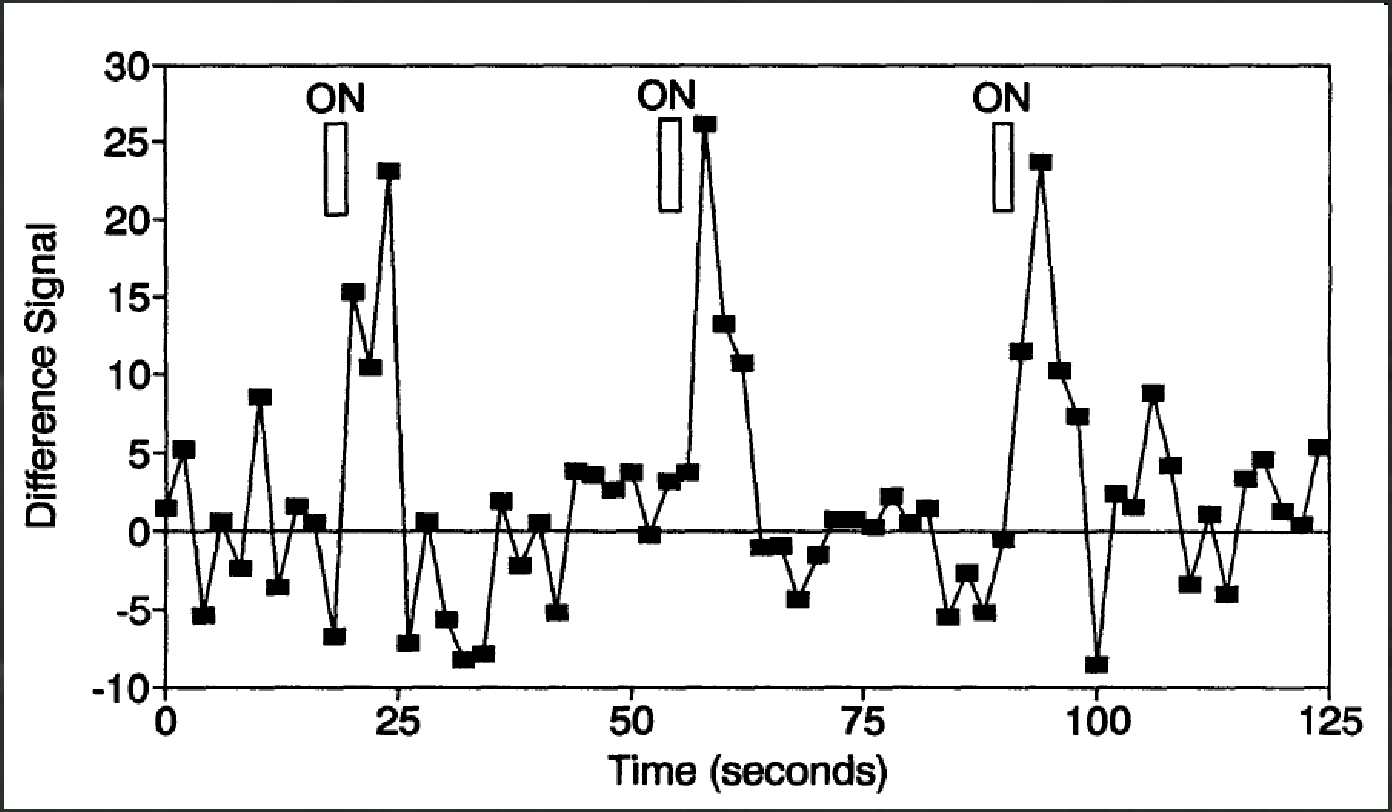
•S. Ogawa, et al., (1992) "Intrinsic signal changes accompanying sensory stimulation: functional brain mapping with magnetic resonance imaging. Proc. Natl. Acad. Sci. USA." 89, 5951-5955.

•P. A. Bandettini, et al., (1992) "Time course EPI of human brain function during task activation." Magn. Reson. Med 25, 390-397.

•Blamire, A. M., et al. (1992). "Dynamic mapping of the human visual cortex by high-speed magnetic resonance imaging." Proc. Natl. Acad. Sci. USA 89: 11069-11073.

Blood Oxygenation

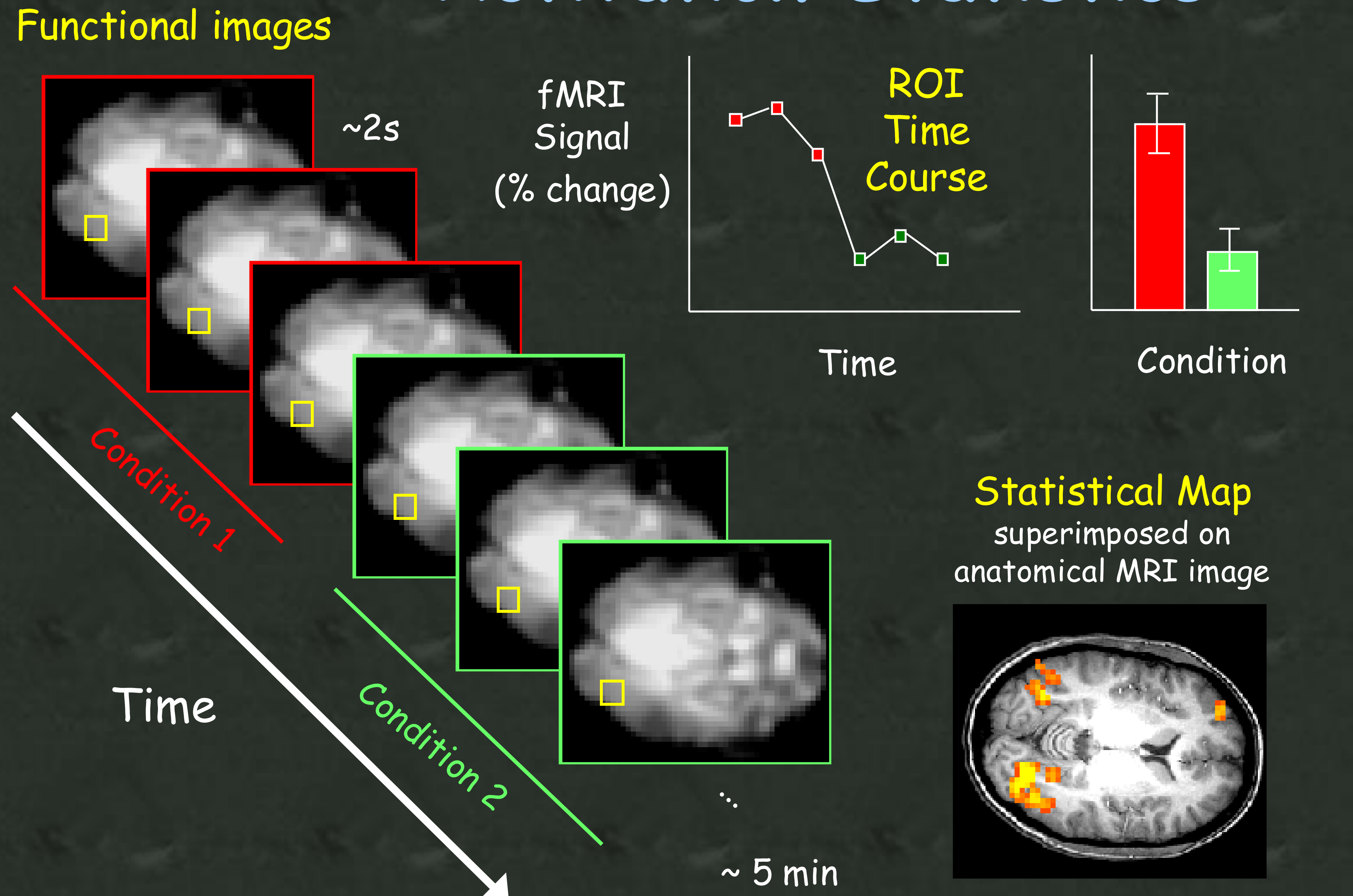
First Event-related fMRI Results



Blamire, A. M., et al. (1992). "Dynamic mapping of the human visual cortex by high-speed magnetic resonance imaging." Proc. Natl. Acad. Sci. USA 89: 11069-11073.

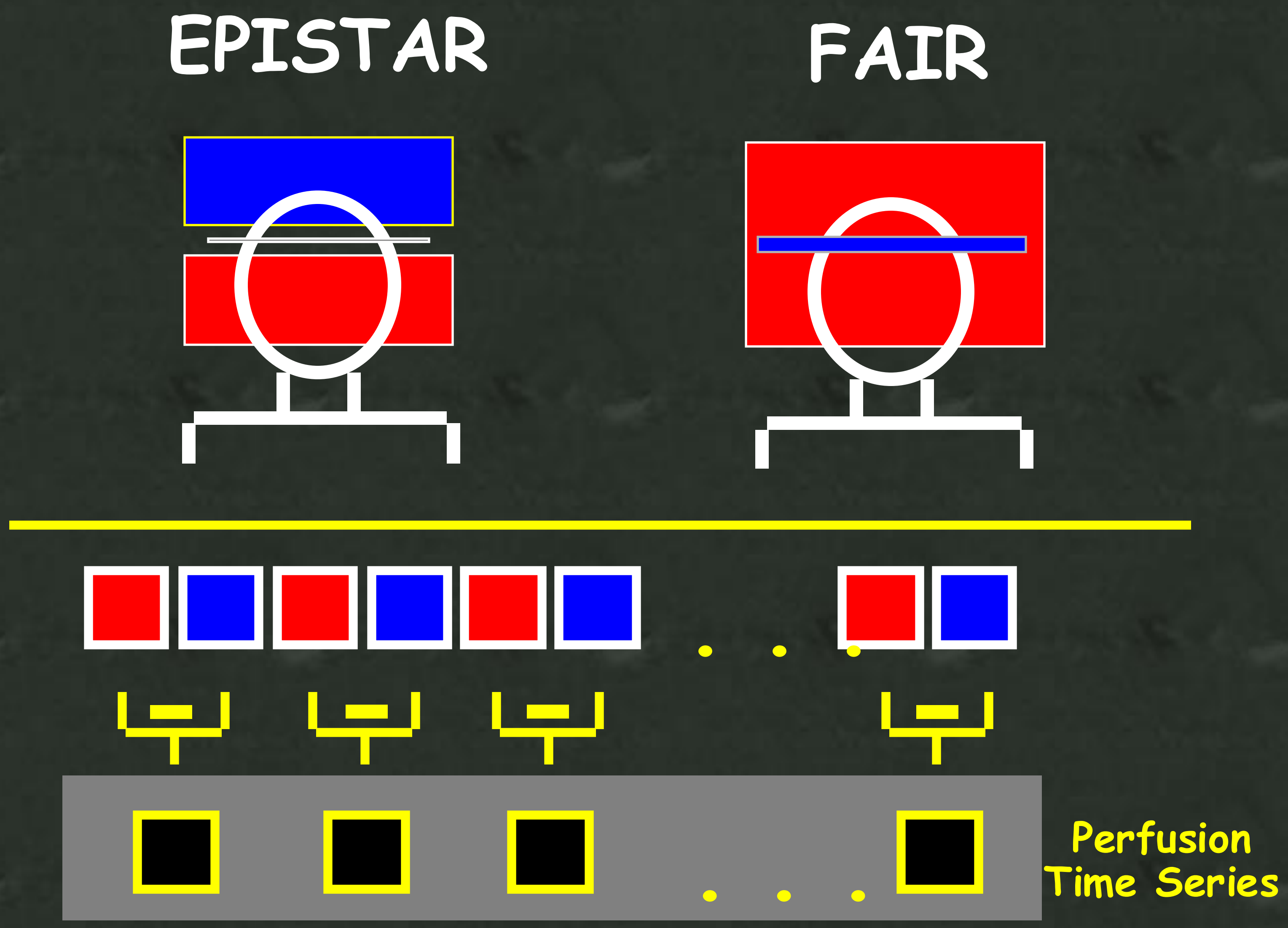
Blood Oxygenation

Activation Statistics



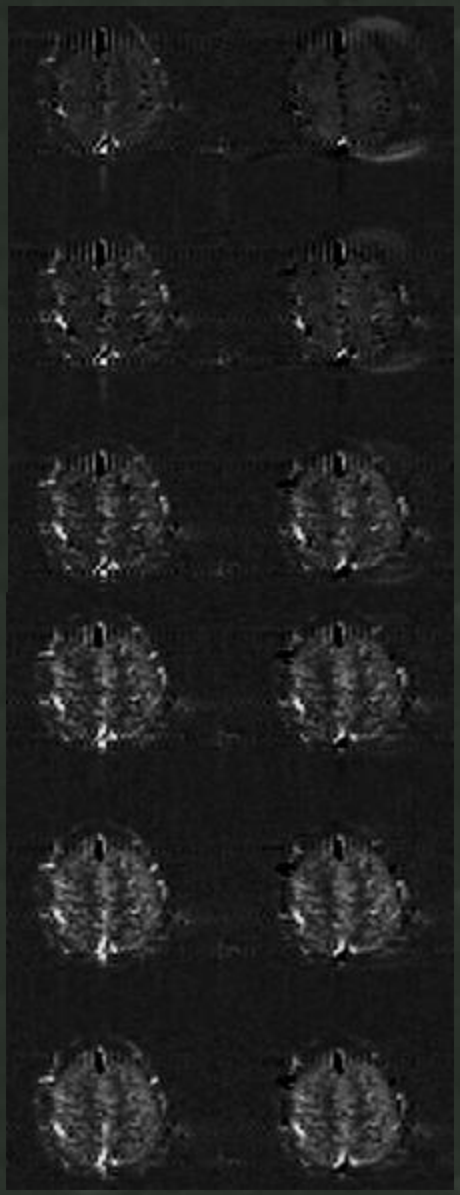
Courtesy, Robert Cox

Perfusion

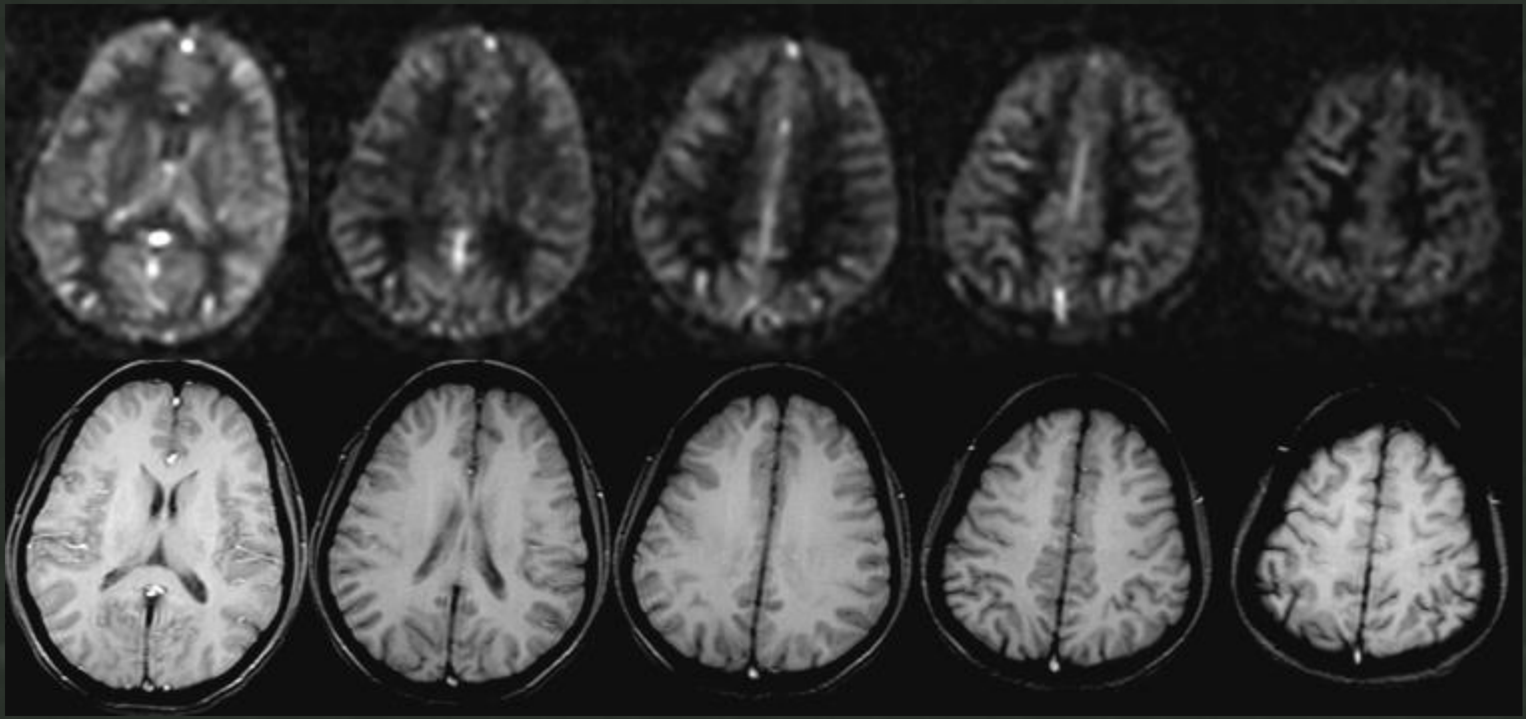


Perfusion

TI (ms)	FAIR	EPISTAR
200		
400		
600		
800		
1000		
1200		



Perfusion



Williams, D. S., Detre, J. A., Leigh, J. S. & Koretsky, A. S. (1992) "Magnetic resonance imaging of perfusion using spin-inversion of arterial water." Proc. Natl. Acad. Sci. USA 89, 212-216.

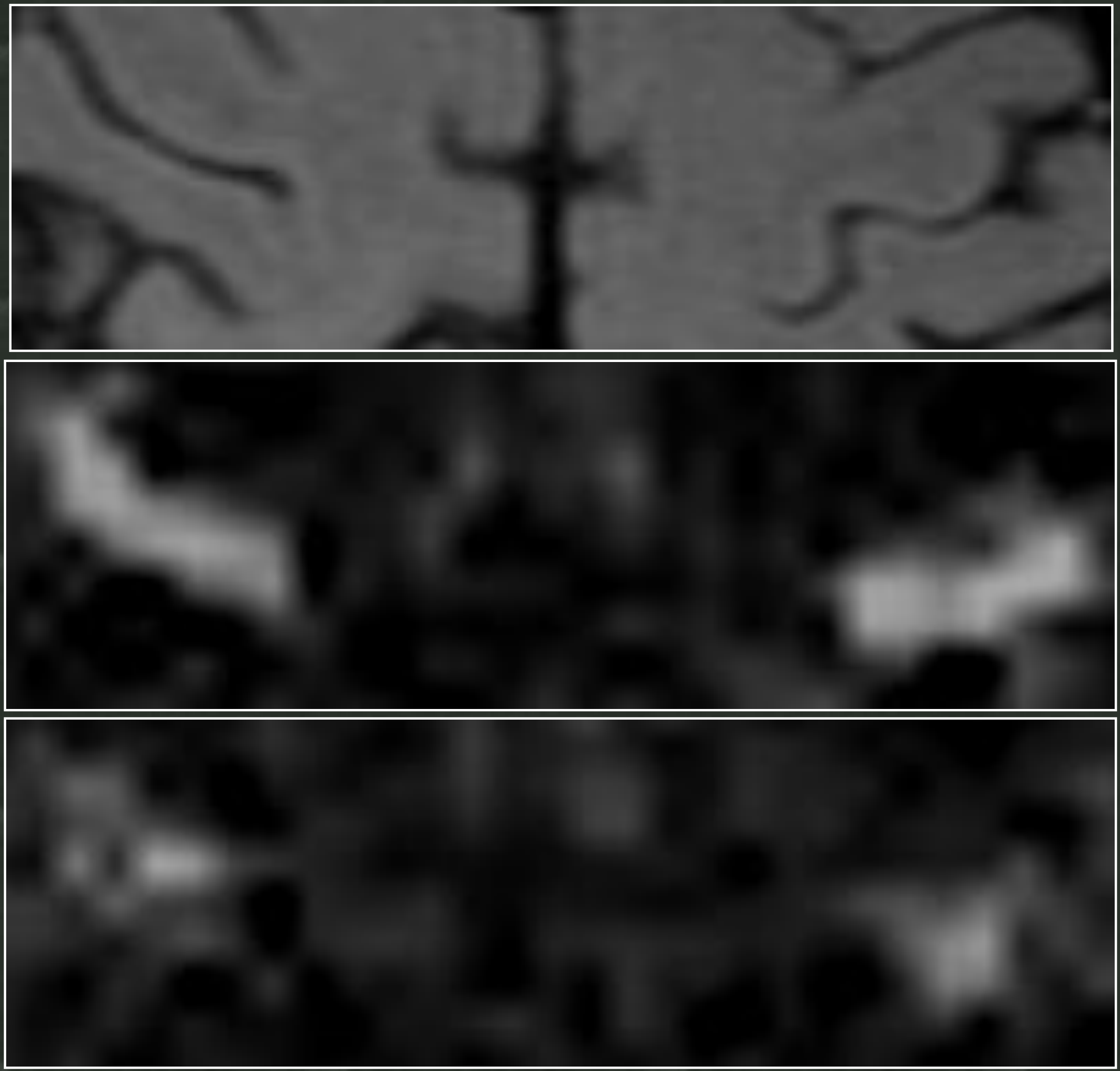
Edelman, R., Siewert, B. & Darby, D. (1994) "Qualitative mapping of cerebral blood flow and functional localization with echo planar MR imaging ans signal targeting with alternating radiofrequency (EPISTAR)." Radiology **192**, 1-8.

Kim, S.-G. (1995) "Quantification of relative cerebral blood flow change by flow-sensitive alternating inversion recovery (FAIR) technique: application to functional mapping." Magn. Reson. Med. **34**, 293-301.

Kwong, K. K. et al. (1995) "MR perfusion studies with T1-weighted echo planar imaging."Magn. Reson. Med. **34**, 878-887.

Perfusion

Simultaneous BOLD and Perfusion

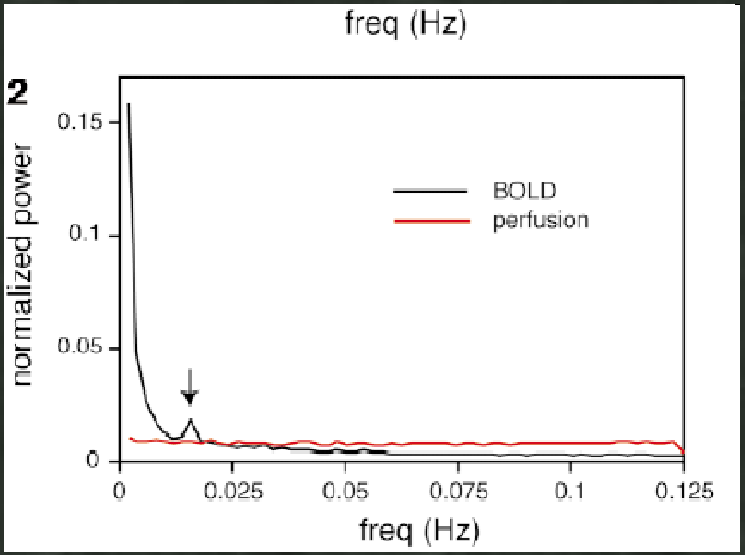


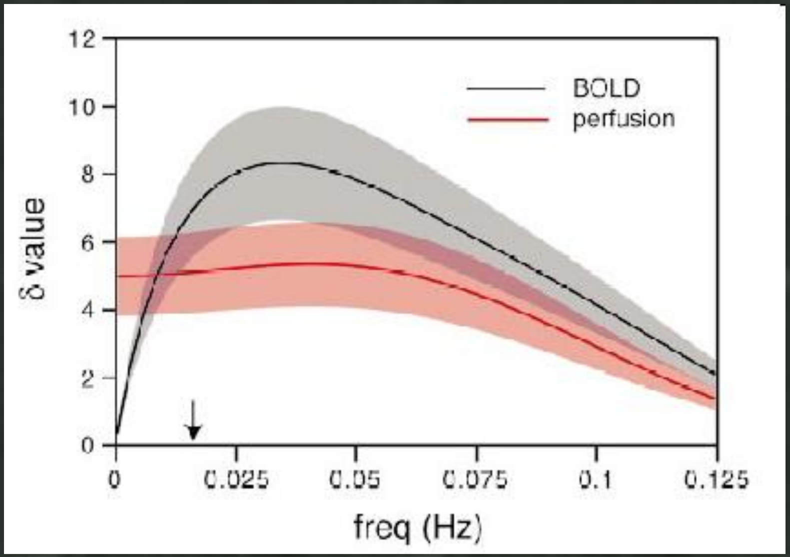
BOLD

Perfusion

Perfusion

Better than BOLD for long duration activation…





GK Aguirre et al, (2002) NeuroImage 15 (3): 488-500

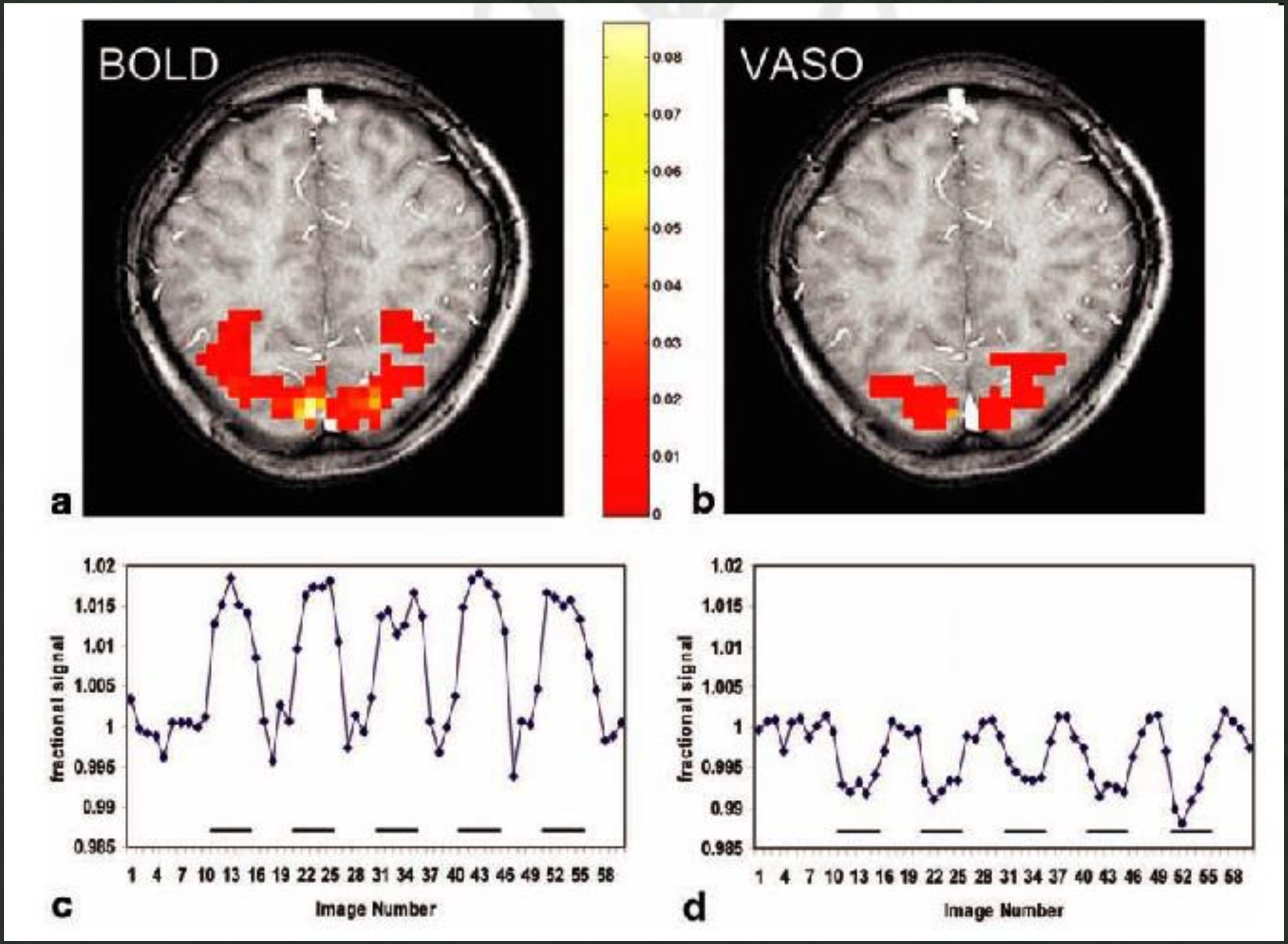
New Contrasts

Non-Invasive Blood Volume Changes

$CMRO_2$ Changes

Direct Neuronal Current Imaging

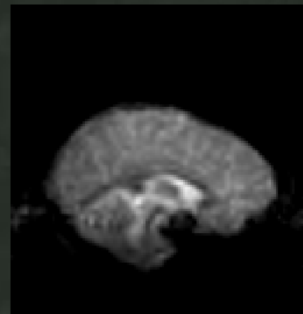
New Contrasts

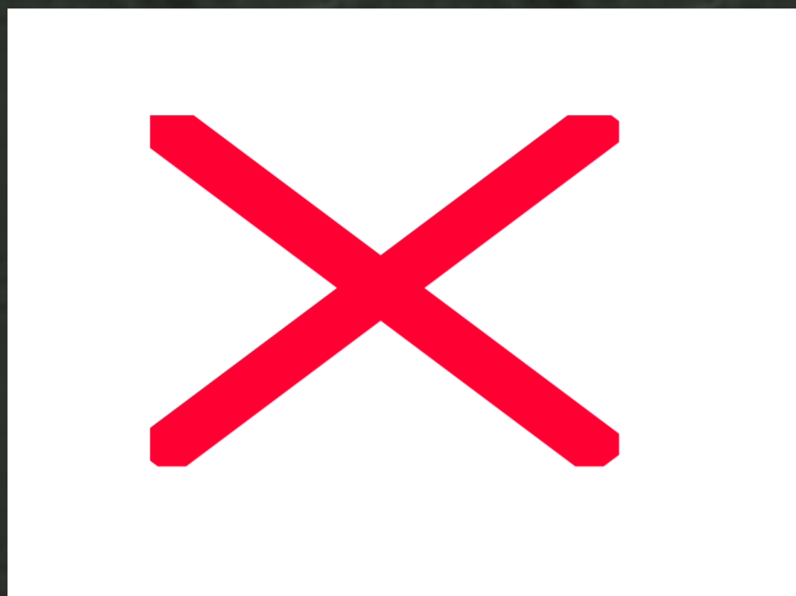


Lu et al, MRM 50 (2): 263-274 (2003)

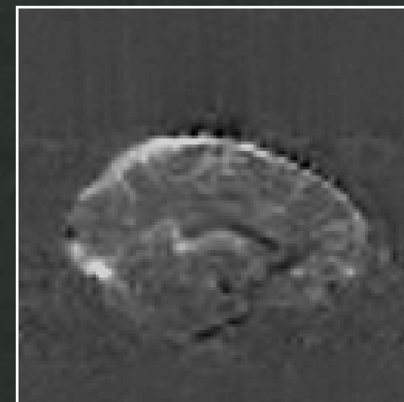
New Contrasts

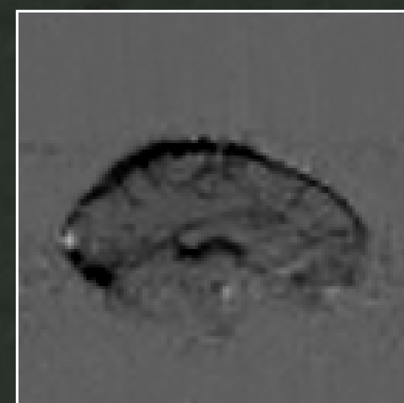
CO_2 or O_2 Stress Blood Volume Mapping





5% CO2





12% O2

P. A. Bandettini, E. C. Wong, A hypercapnia - based normalization method for improved spatial localization of human brain activation with fMRI. *NMR in Biomedicine* 10, 197-203 (1997).

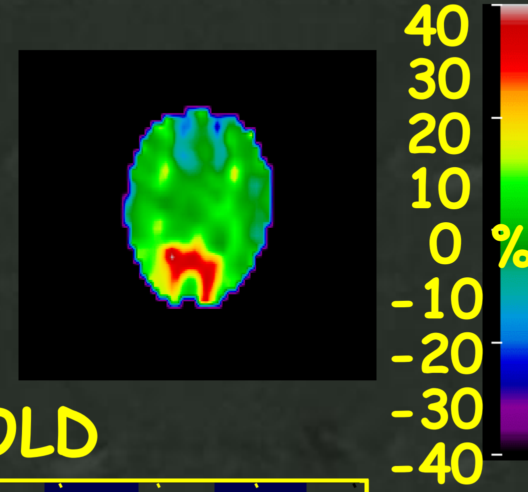
New Contrasts

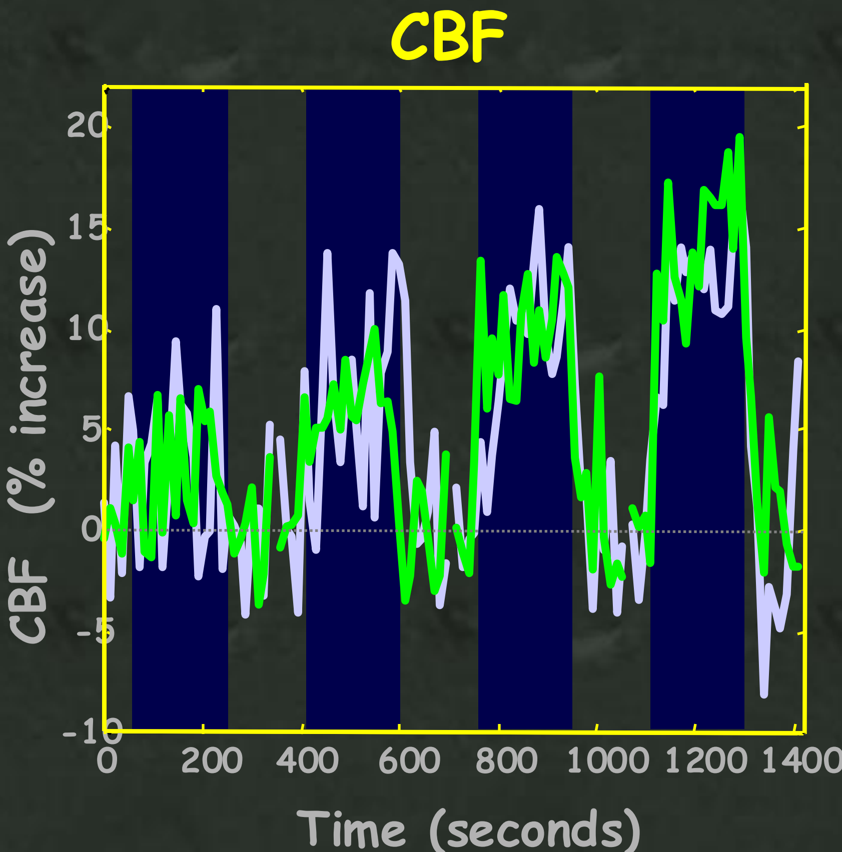
Proc. Natl. Acad. Sci. USA
Vol. 96, pp. 9403–9408, August 1999
Neurobiology

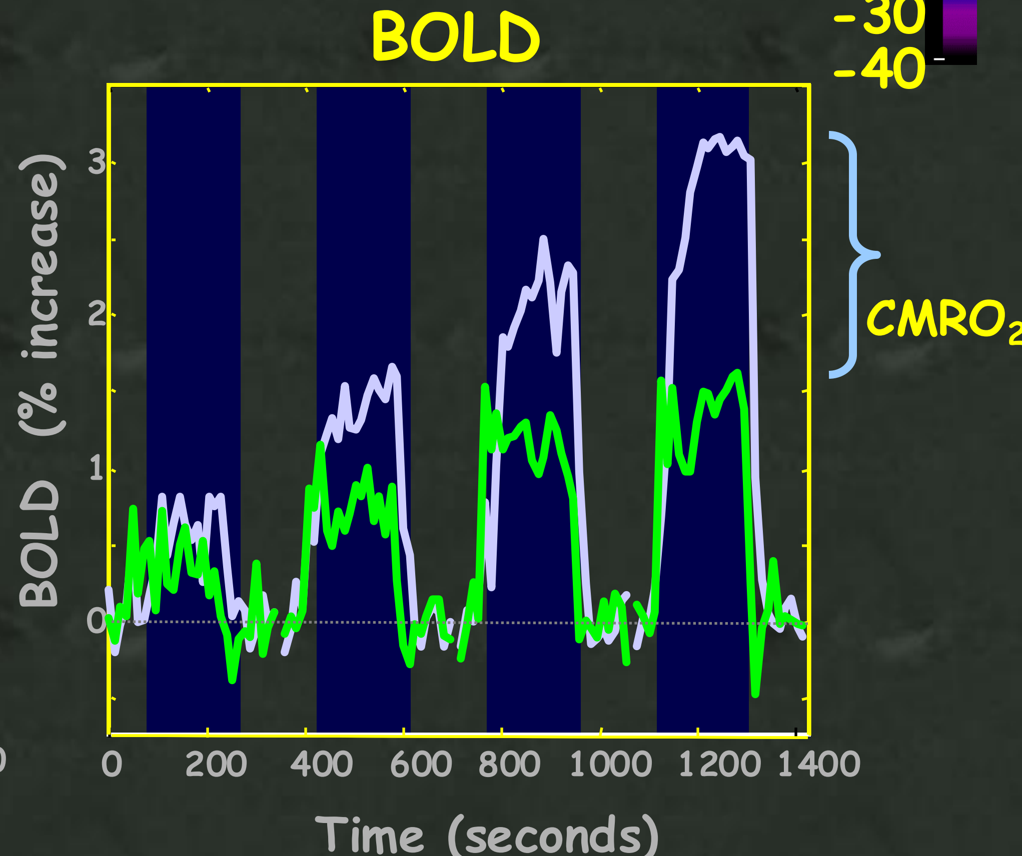
Linear coupling between cerebral blood flow and oxygen consumption in activated human cortex

Richard D. Hoge*†, Jeff Atkinson*, Brad Gill*, Gérard R. Crelier*, Sean Marrett‡, and G. Bruce Pike*

*Room WB325, McConnell Brain Imaging Centre, Montreal Neurological Institute, Quebec, Canada H3A 2B4; and ‡Nuclear Magnetic Resonance Center, Massachusetts General Hospital, Building 149, 13th Street, Charlestown, MA 02129





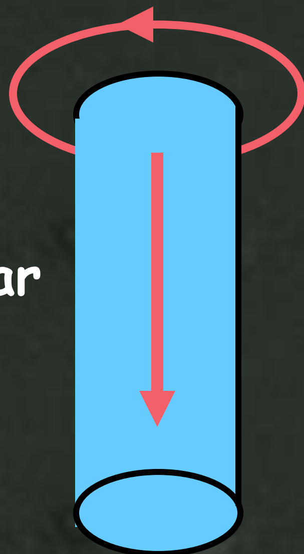


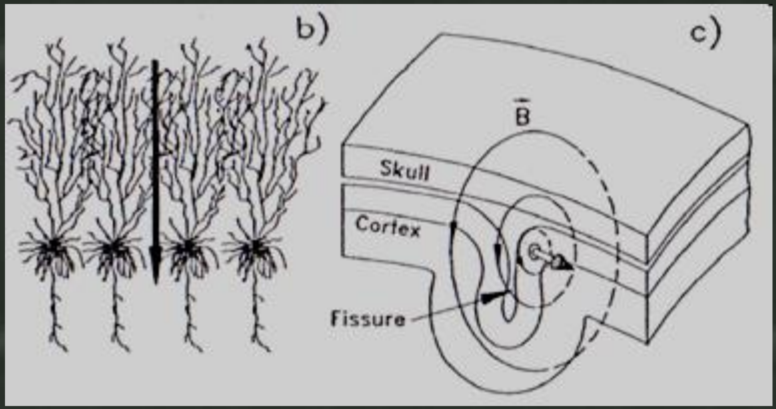
Simultaneous Perfusion and BOLD imaging during graded visual activation and hypercapnia

New Contrasts

Magnetic Field

Intracellular Current

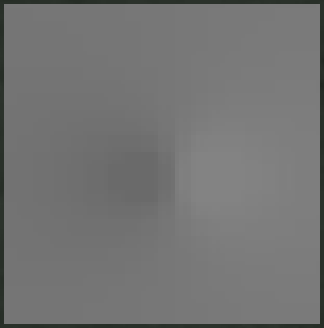


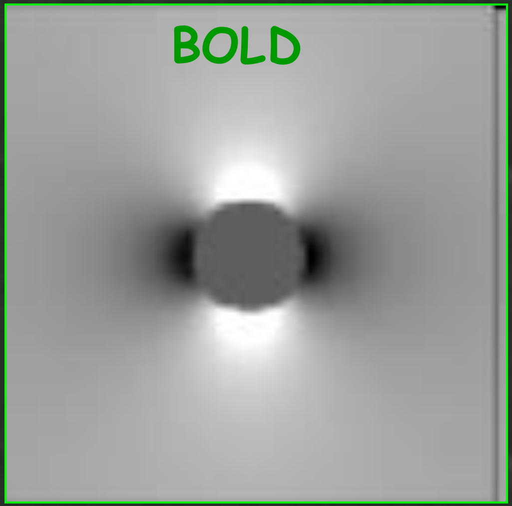


100 fT at on surface of skull

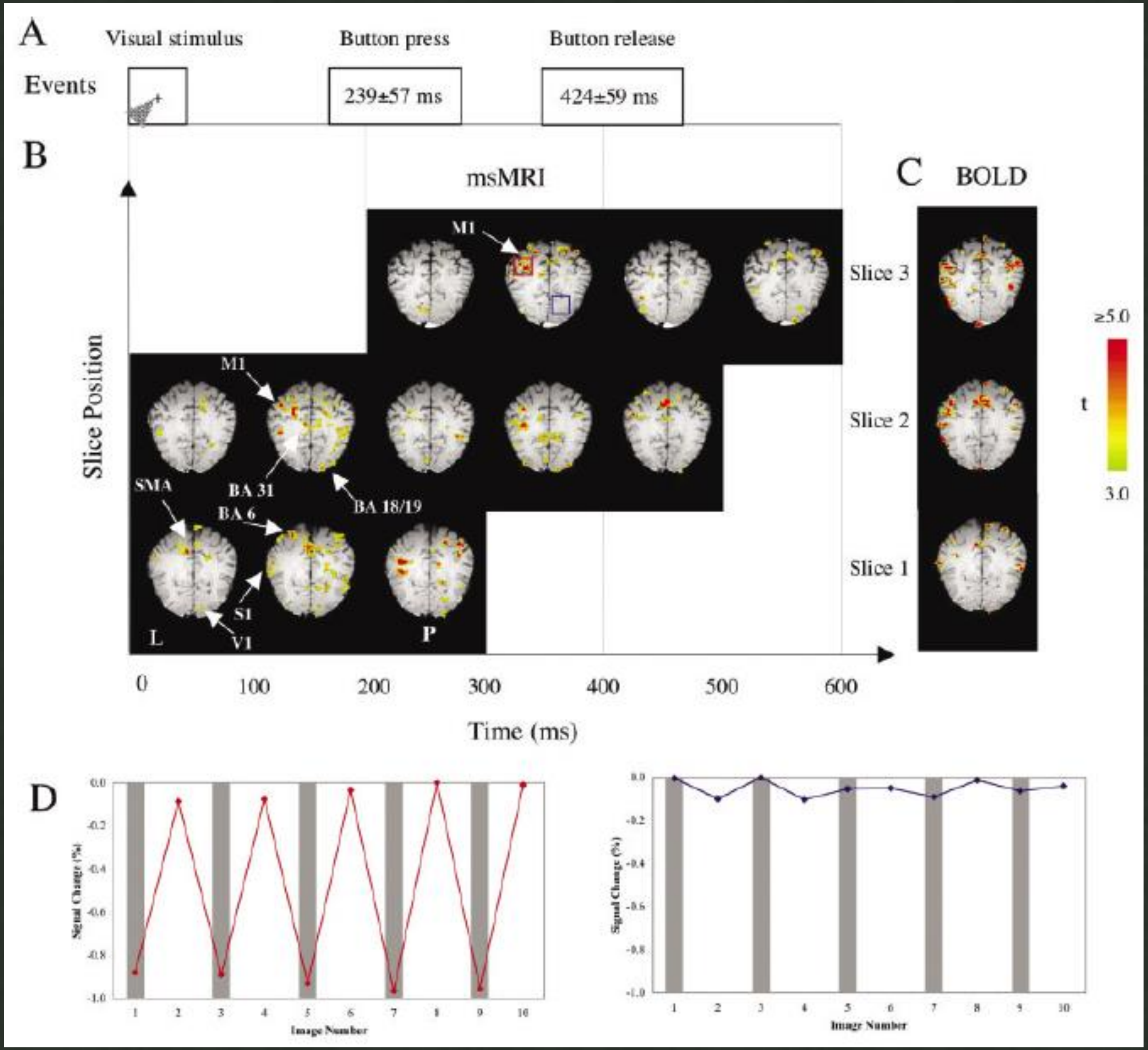
And 0.2 nT near source

Surface Fields





New Contrasts

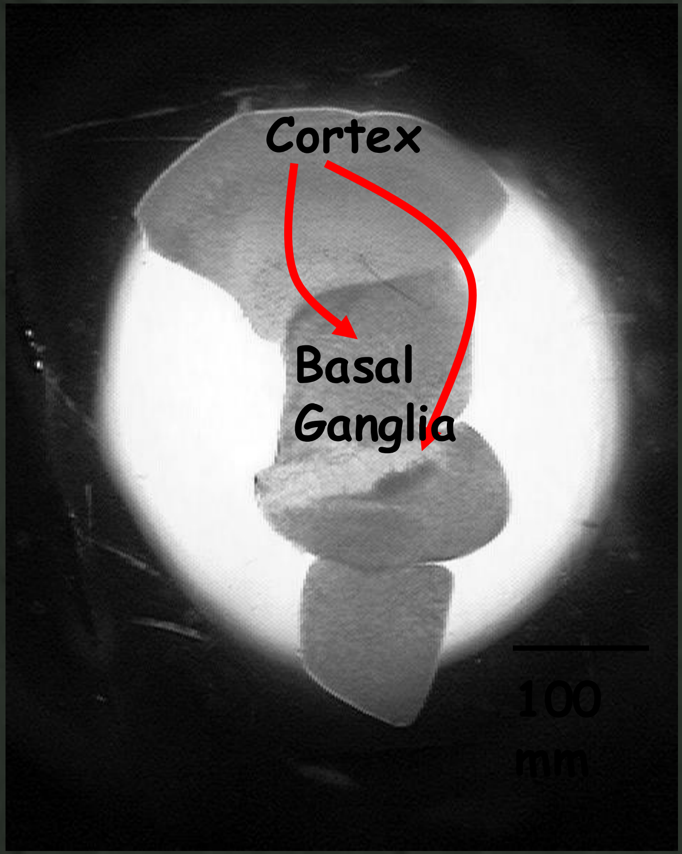


J. Xiong, P. T. Fox, J.-H. Gao, *Direct MRI Mapping of neuronal activity.* **Human Brain Mapping, 20: 41-49, (2003)**

New Contrasts

In Vitro Results

Organotypic (*no blood supply or hemoglobin traces*) sections of newborn-rat somato-sensory Cortex, or somato-sensory Cortex & Basal Ganglia

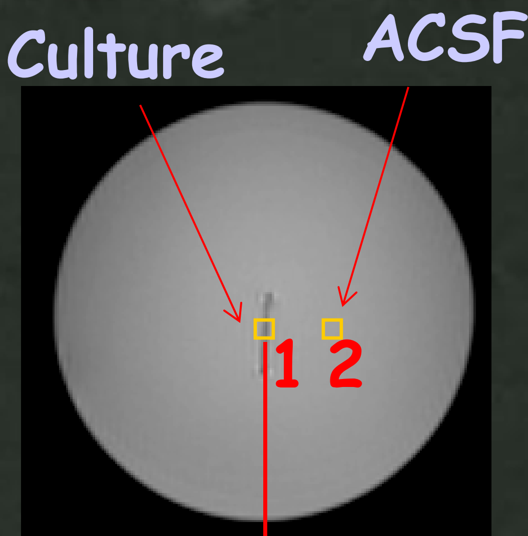


- Size: in-plane:~1-2mm^2, thickness: 60-100μm
- Neuronal Population: 10,000-100,000

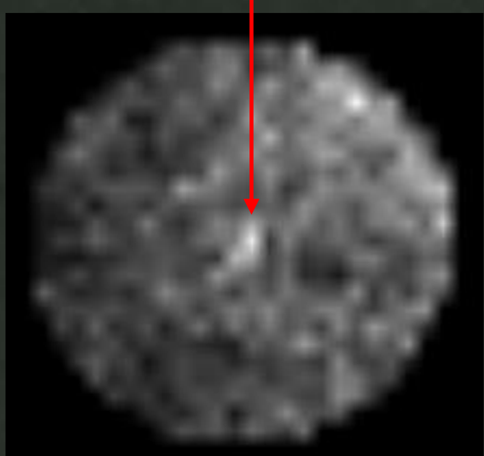
- Spontaneous synchronized activity < 2Hz
- Epileptiform activity
- Spontaneous beta freq. activity (20-30Hz)
- Network Activity Range: ~ 0.5-15μV

Plenz, D. et al. *Neurosci* 70(4): 861-924, 1996

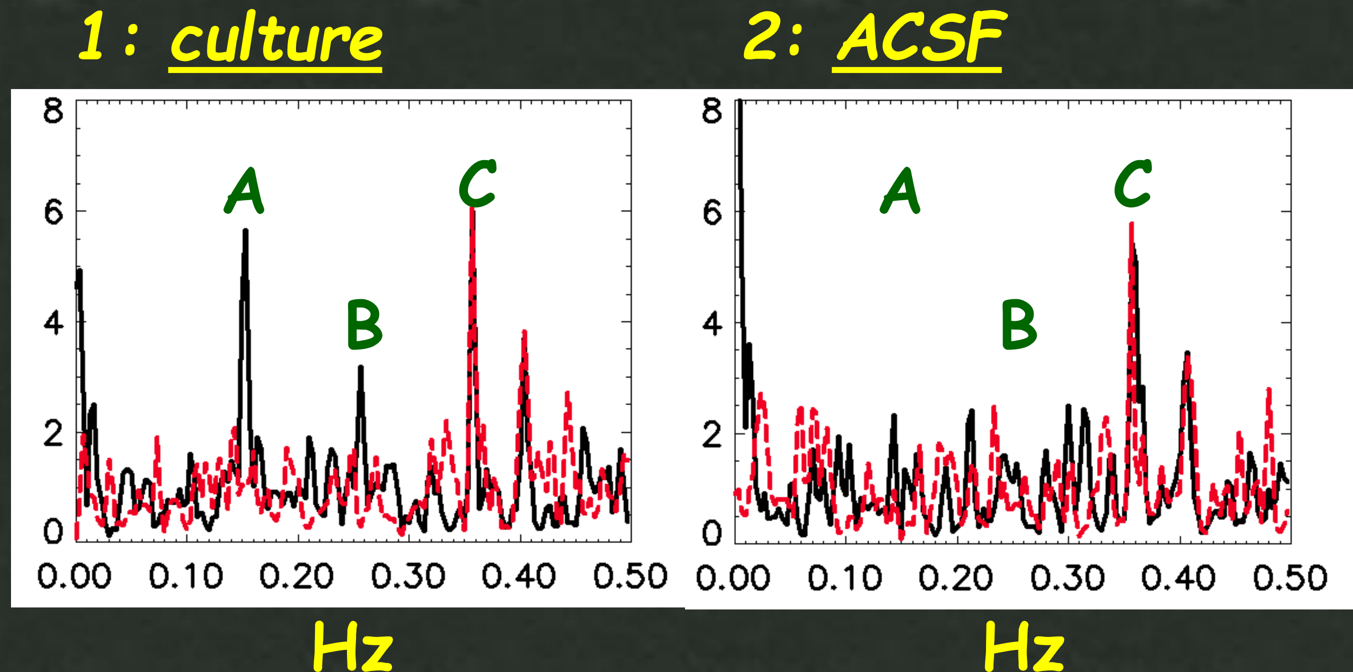
New Contrasts



FSE image



0.15Hz map



Active condition: black line
Inactive condition: red line

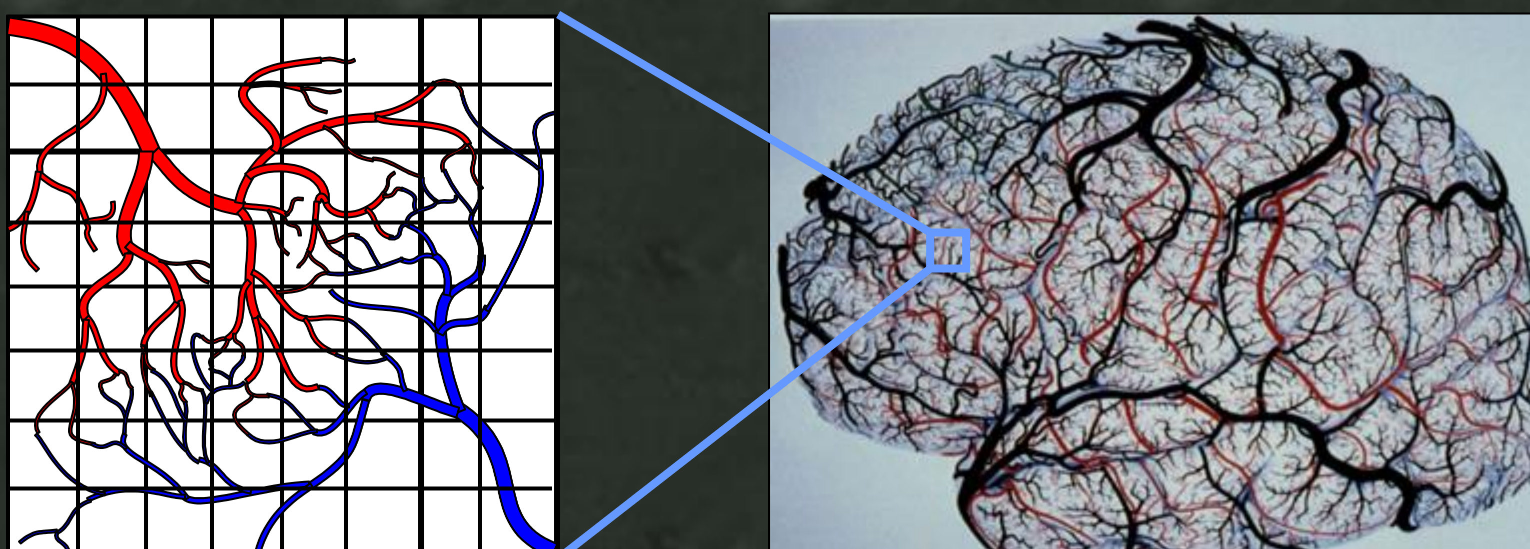
A: 0.15 Hz activity, on/off frequency
B: activity
C: scanner noise (cooling-pump)

The HRF

Neuronal Activation → ? → Measured Signal

Neuronal Activation → ? → Hemodynamics → ? → Measured Signal

Noise → ? → Measured Signal

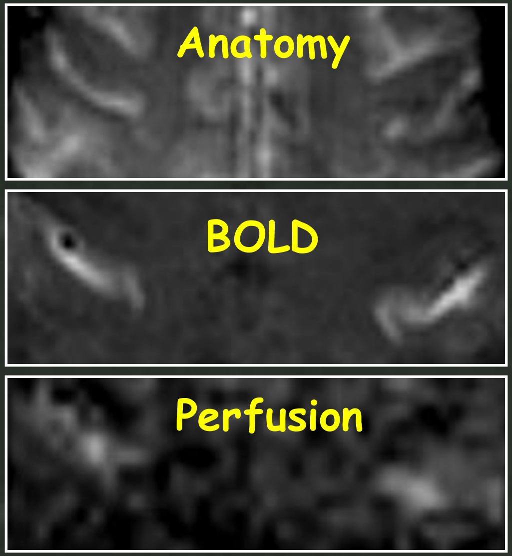


Altered neurovascular coupling: Pathology, drugs

Pathologic state / Drug	Reference
Carotid occlusion	Röther et al. 2002
Transient global ischemia	Schmitz et al. 1998
Penumbra of cerebral ischemia	Mies et al. 1993, Wolf et al. 1997
Subarachnoid hemorrhage	Dreier et al. 2000
Trauma	Richards et al. 2001
Epilepsy	Fink et al. 1996, Brühl et al. 1998, von Pannwitz et al. 2002
Alzheimer´s disease	Hock et al. 1996, Niwa et al. 2000
Theophylline	Ko et al. 1990, Dirnagl et al. 1994
Scopolamine	Tsukada et al. 1998

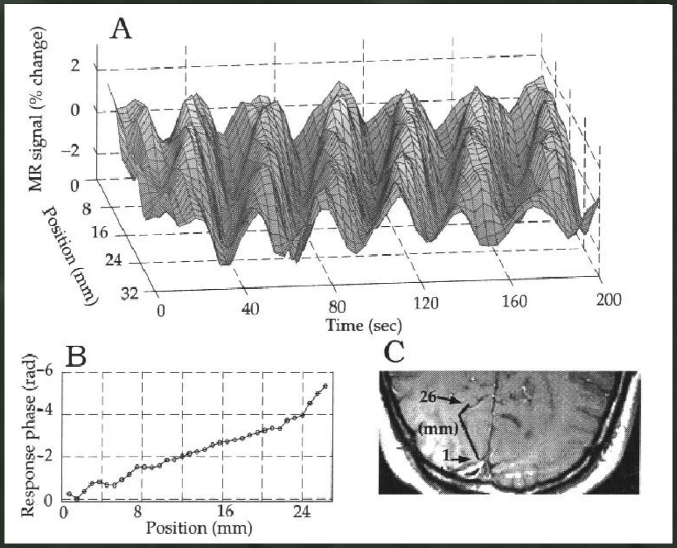
Courtesy of Arno Villringer

The HRF: Spatial and Temporal Resolution



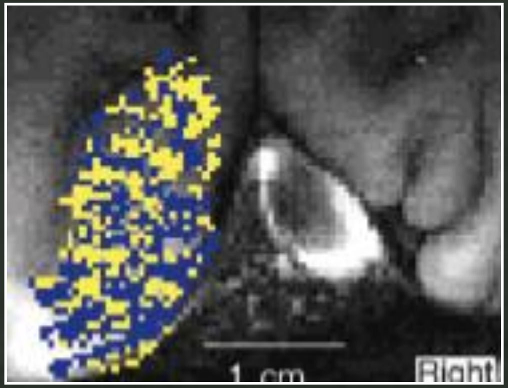
P. A. Bandettini, (1999) "Functional MRI" 205-220.

PSF FWHM = 3.5mm



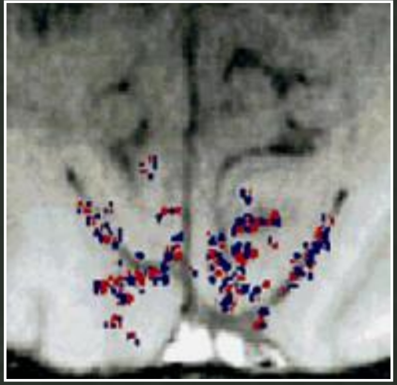
S.A. Engel, et al. Investigative Ophthalmology & Visual Science 35 (1994) 1977-1977.

0.47 x 0.47 in plane resolution



Cheng, et al. (2001) Neuron,32:359-374

0.54 x 0.54 in plane resolution

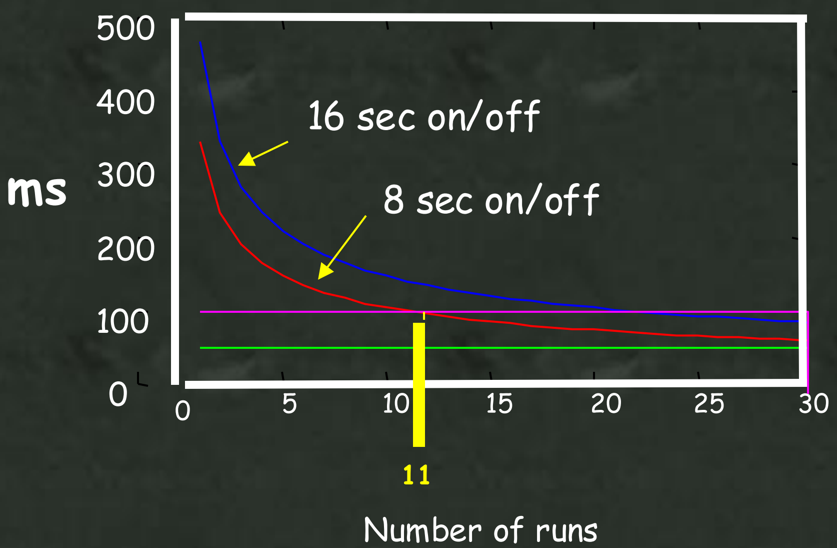


Multi-shot with navigator pulse

Menon et al, (1999) MRM 41 (2): 230-235

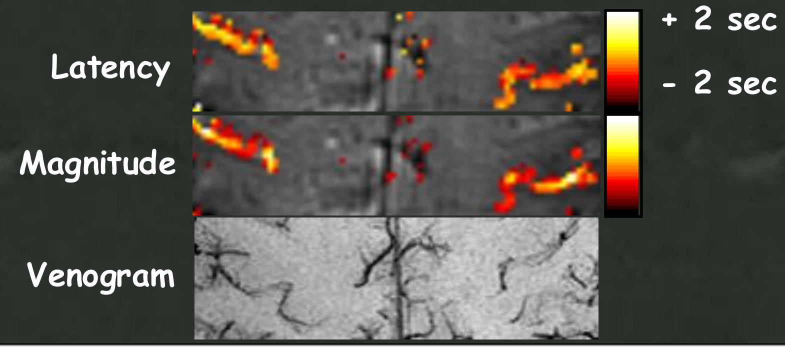
The HRF: Spatial and Temporal Resolution

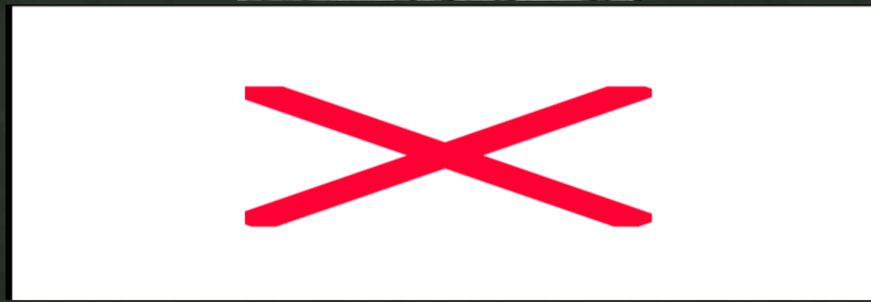
In an ideal world… no latency variation



R. Birn

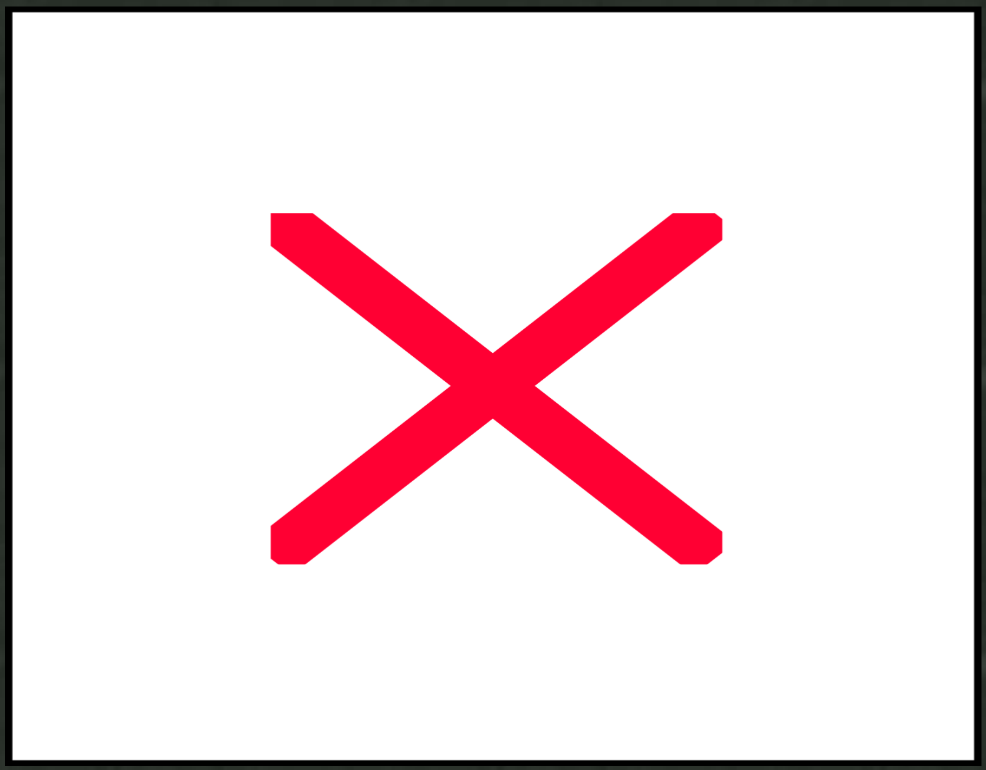
Latency Variation…





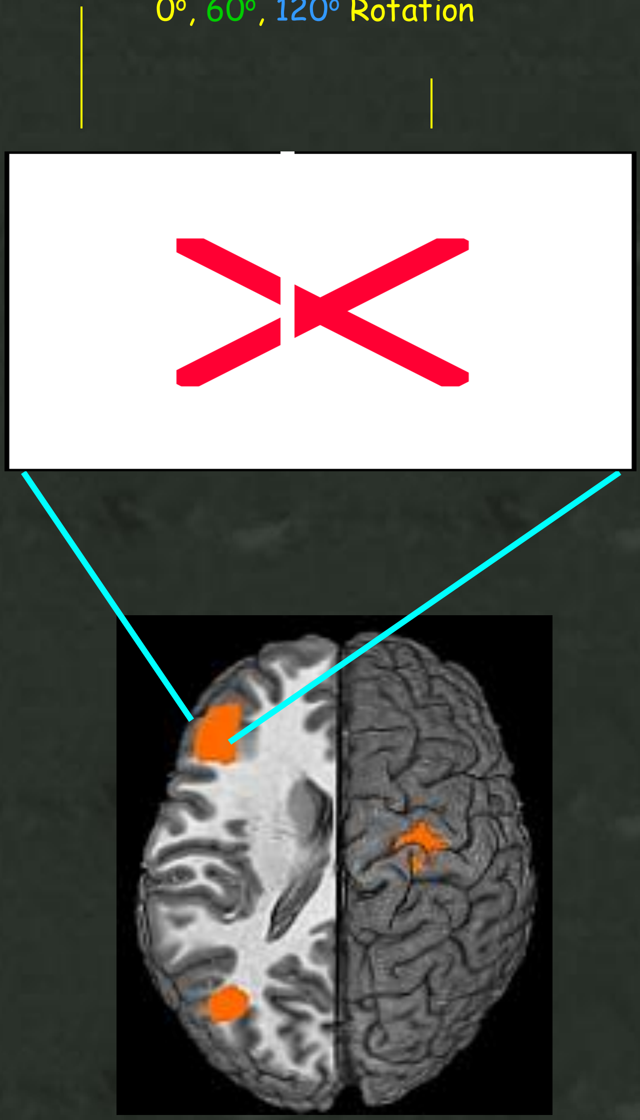
P. A. Bandettini, (1999) "Functional MRI" 205-220.

The HRF: Spatial and Temporal Resolution



Word vs. Non-word

0°, 60°, 120° Rotation



Bellgowan, et al (2003), PNAS 100, 15820-15283

fMRI Contrast

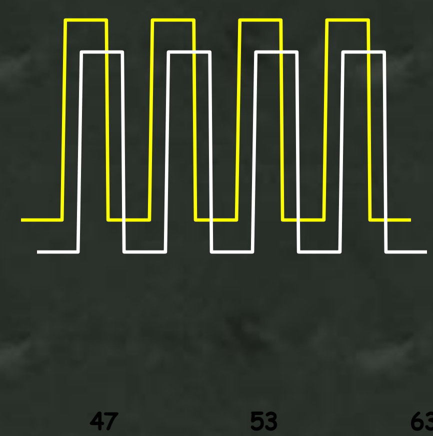
Blood Volume
Blood Oxygenation
Perfusion
New Contrasts
The HRF: Spatial and Temporal Resolution

fMRI Methodology

Paradigm Design
Sensitivity and Noise

Neuronal Activa… Strategies

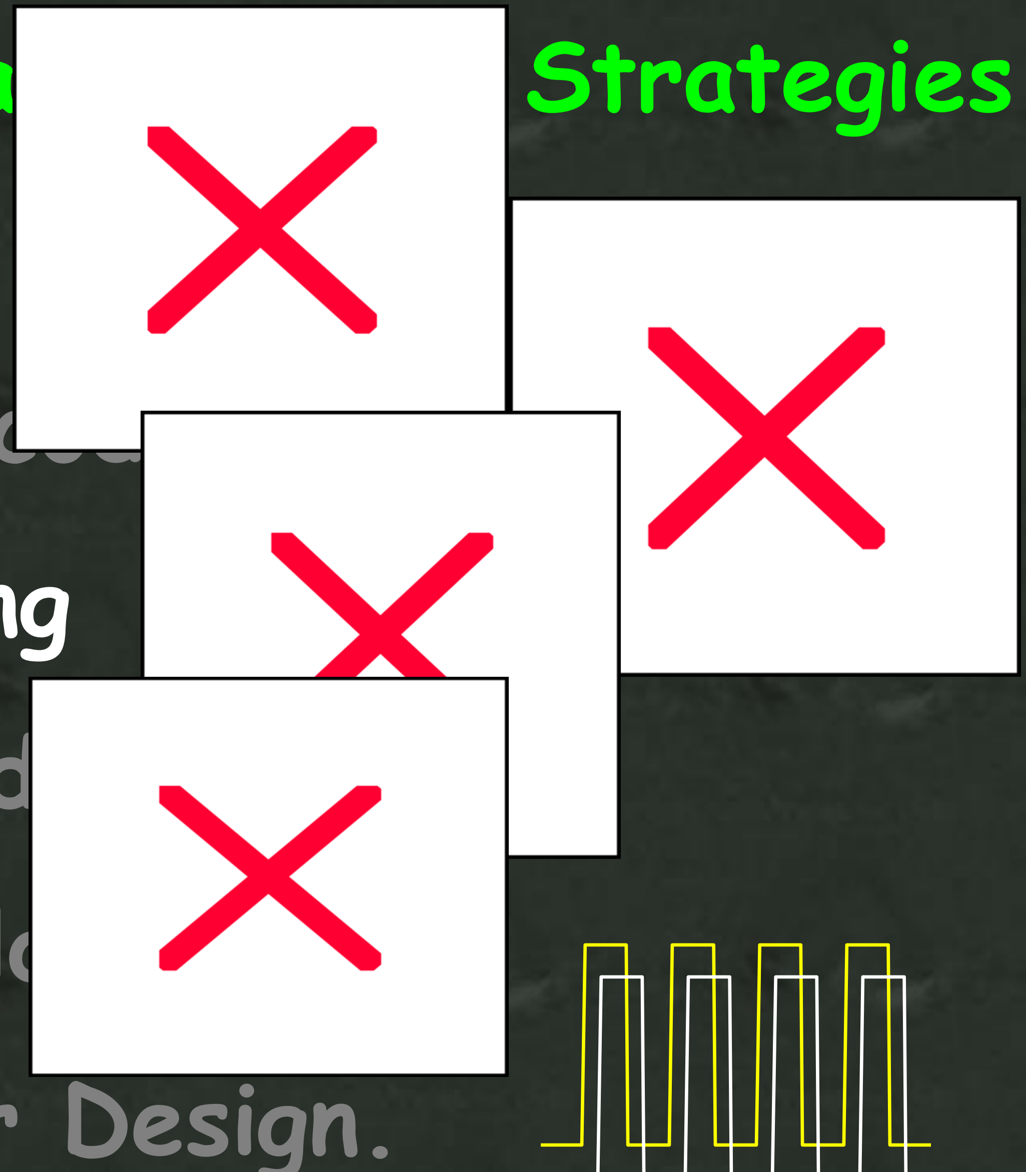
1. Block Design
2. Frequency Enc…
3. Phase Encoding
4. Event-Related
5. Orthogonal Bl…
6. Free Behavior Design.



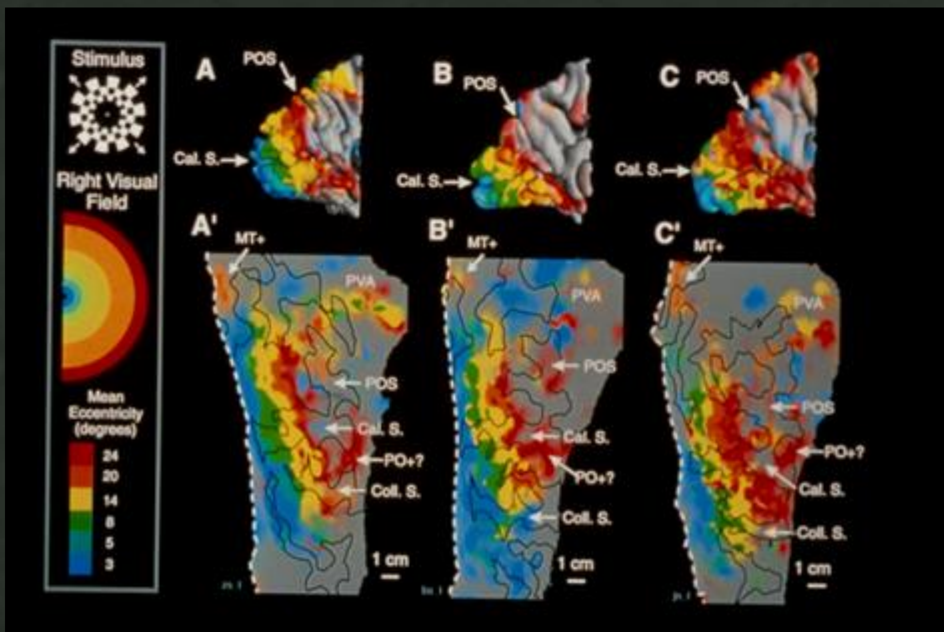
Paradigm Design

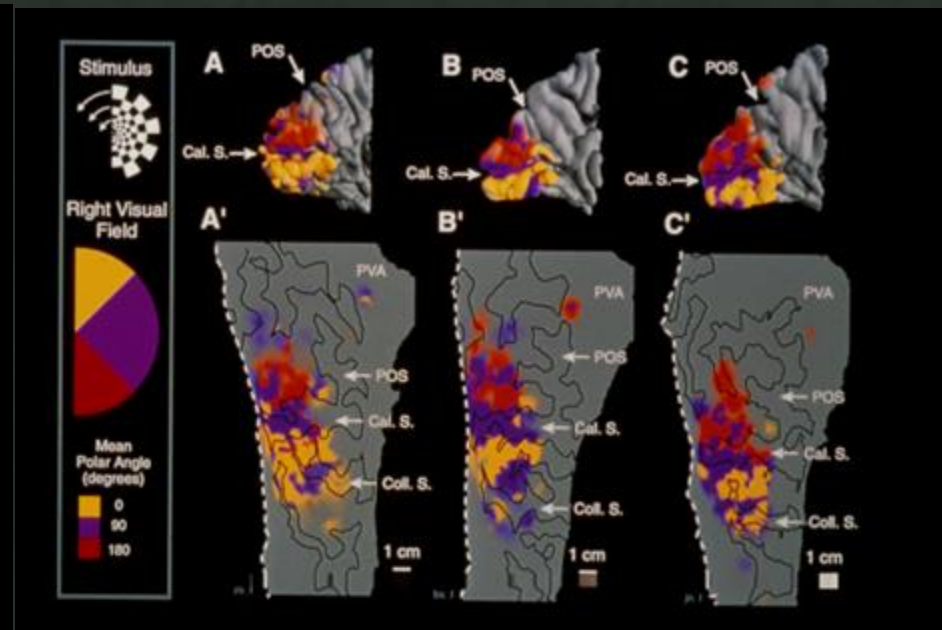
Neuronal Activa Strategies

1. Block Design
2. Frequency Enc
3. **Phase Encoding**
4. Event-Related
5. Orthogonal Bl
6. Free Behavior Design.



Paradigm Design





E.A. DeYoe, et al, PNAS 93 (1996) 2382-2386.

Neuronal Activa Strategies

1. Block Design
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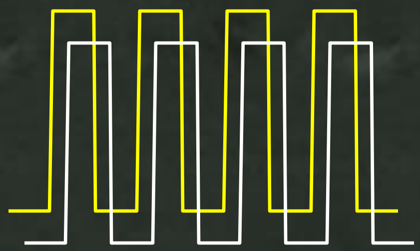
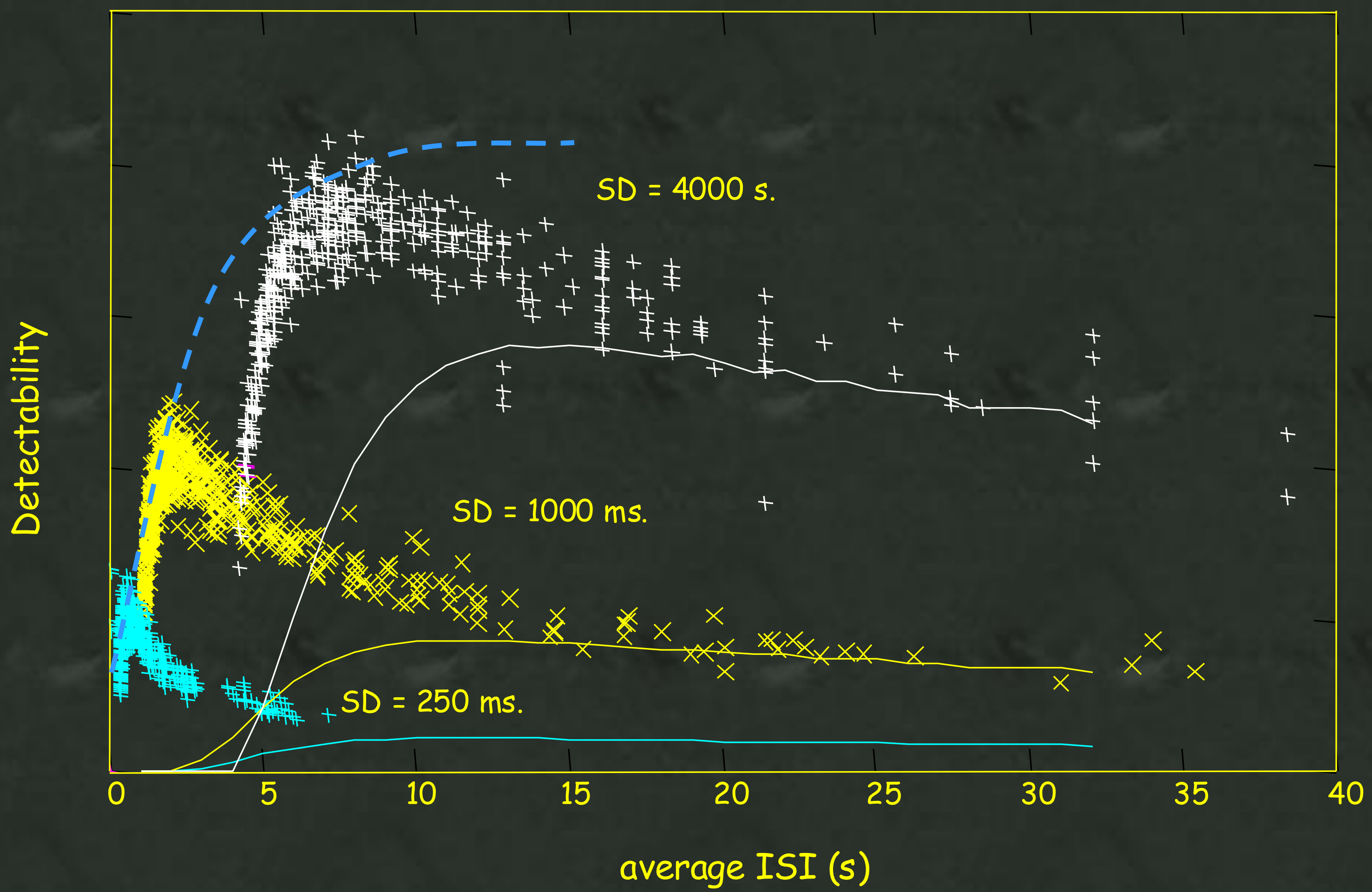


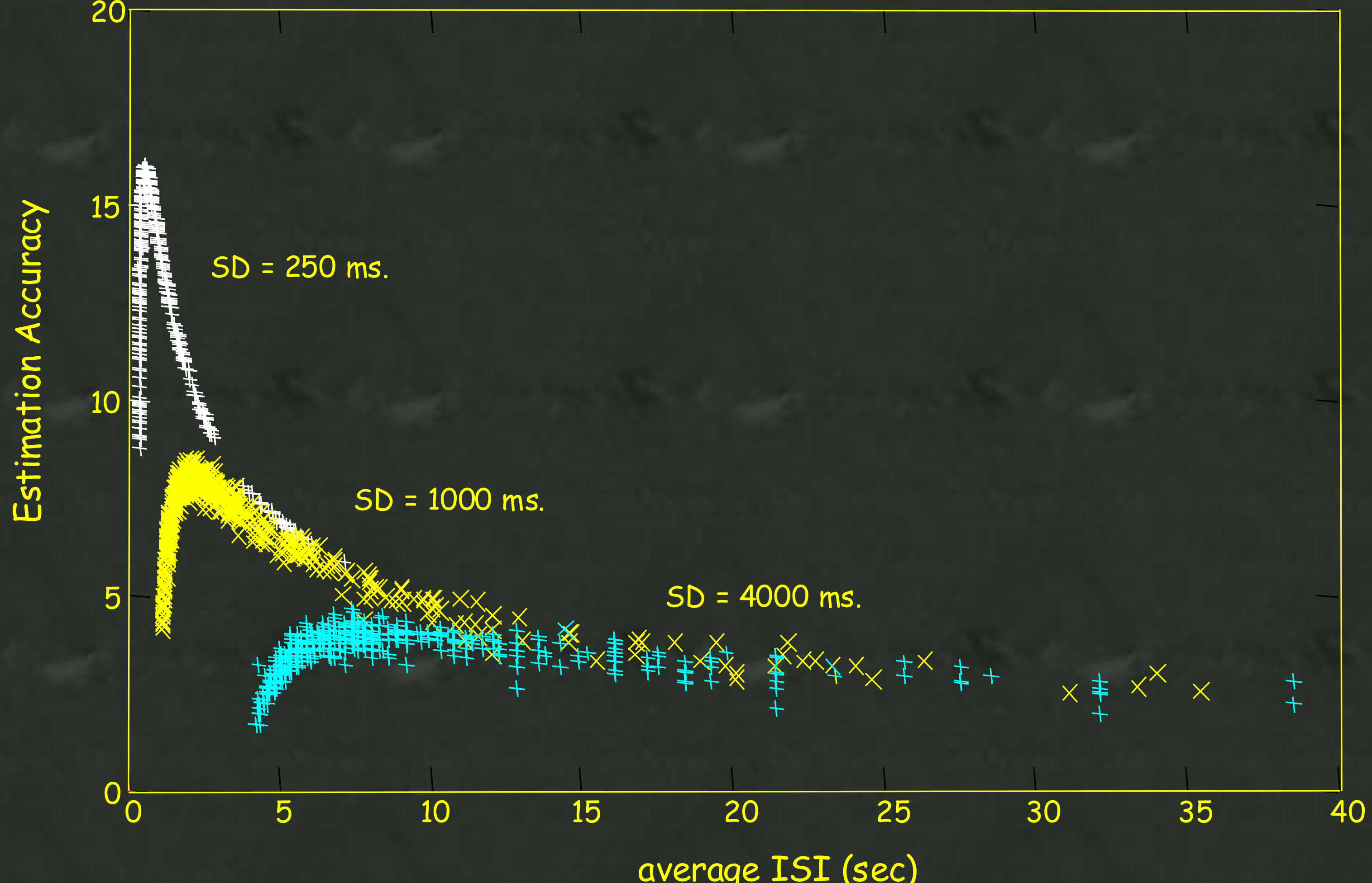
Detectability vs. Average ISI



R. M. Birn, et al. *NeuroImage* **15: 262-264, (2002).**

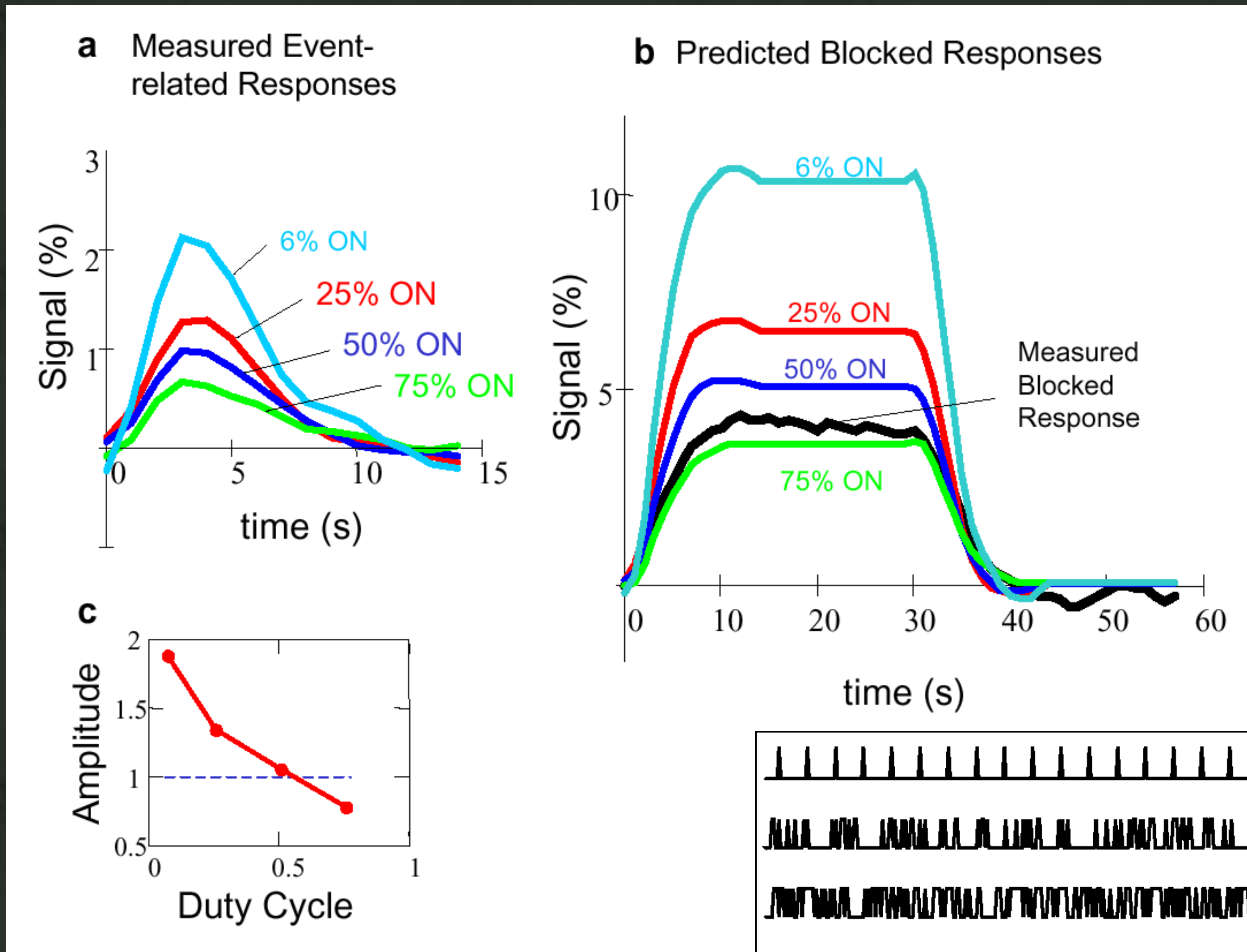
Paradigm Design

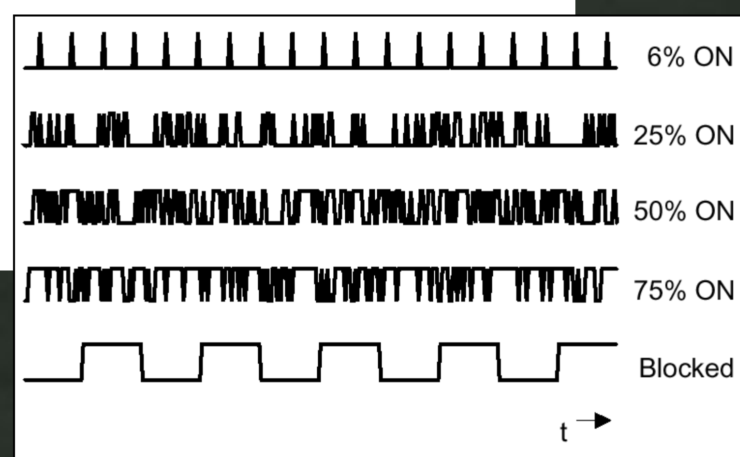
Estimation accuracy vs. average ISI



R. M. Birn, et al. *NeuroImage* **15: 262-264, (2002).**

Paradigm Design





R.M. Birn, P. A. Bandettini. *NeuroImage, (in press)*

Neuronal Activa Strategies

1. Block Design
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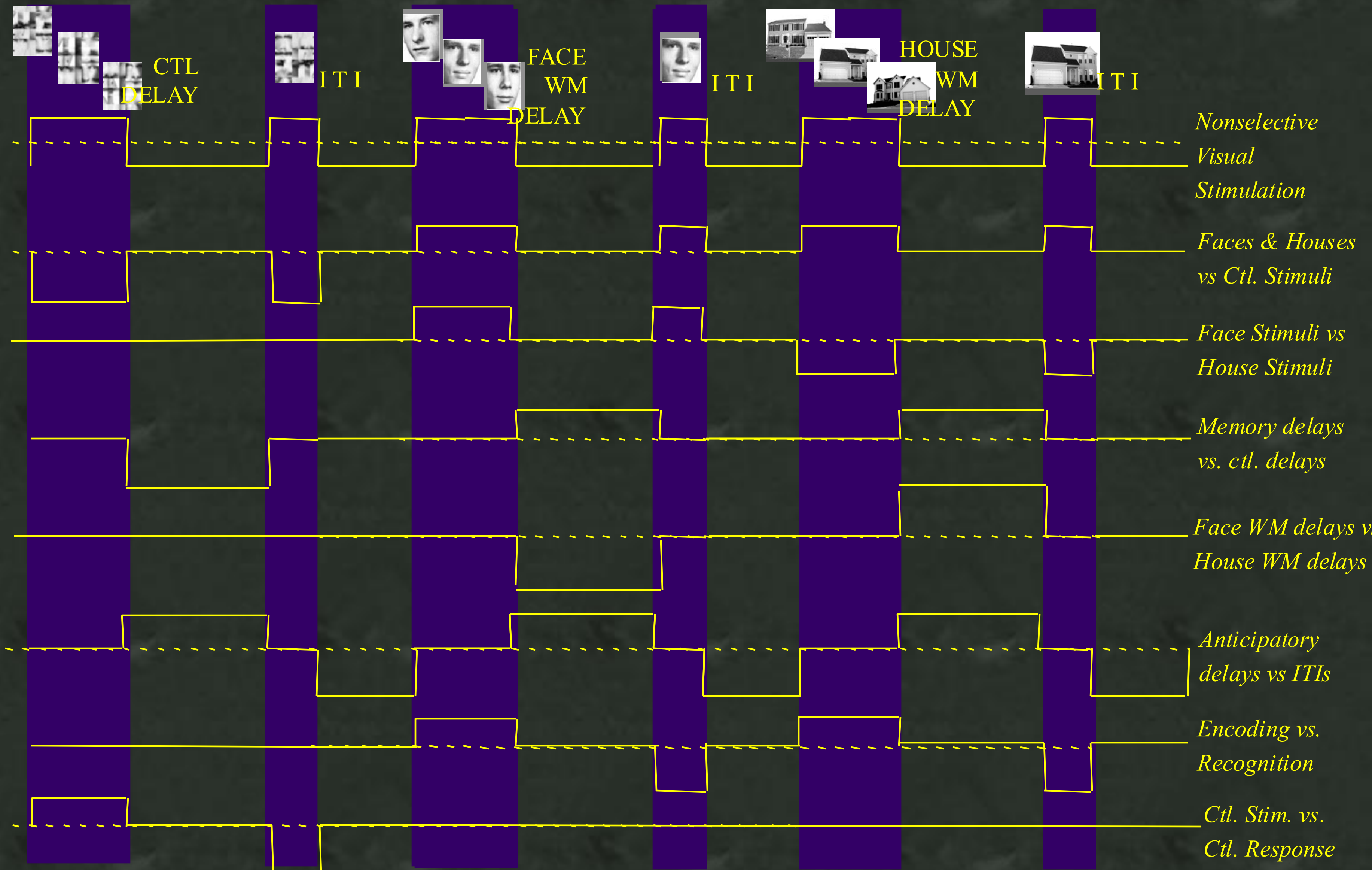
4. Event-Related
5. **Orthogonal Bl**
6. Free Behavior Design.

Paradigm Design

Example of a Set of Orthogonal Contrasts for Multiple Regression



S.M. Courtney, Nature 386 (1997) 608-611.

Neuronal Activa Strategies

1. Block Design
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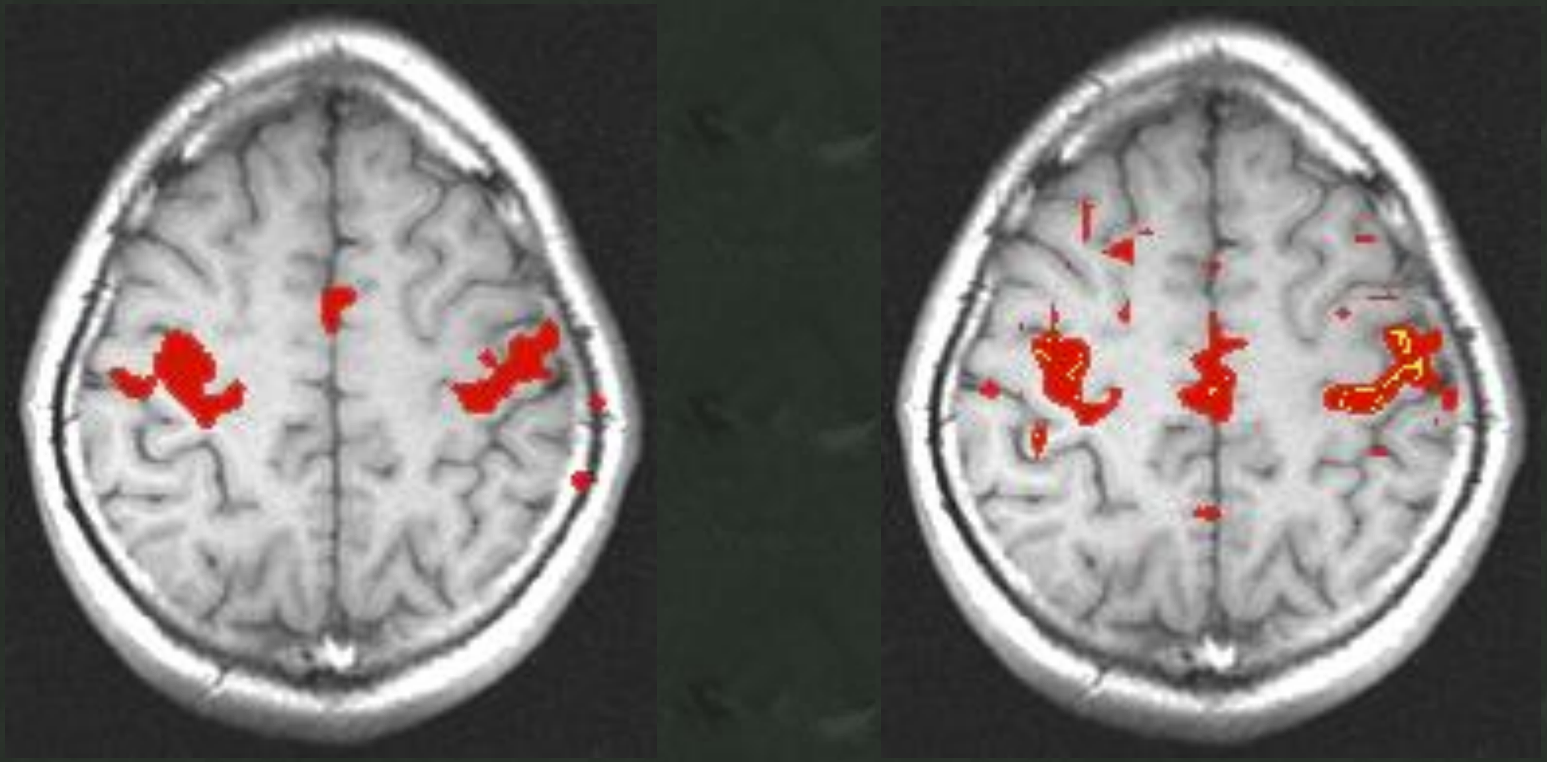
6. Free Behavior Design.

Paradigm Design

Resting State Correlations



Activation:
correlation with reference function

Rest:
seed voxel in motor cortex

B. Biswal *et al.*, MRM, 34:537 (1995)

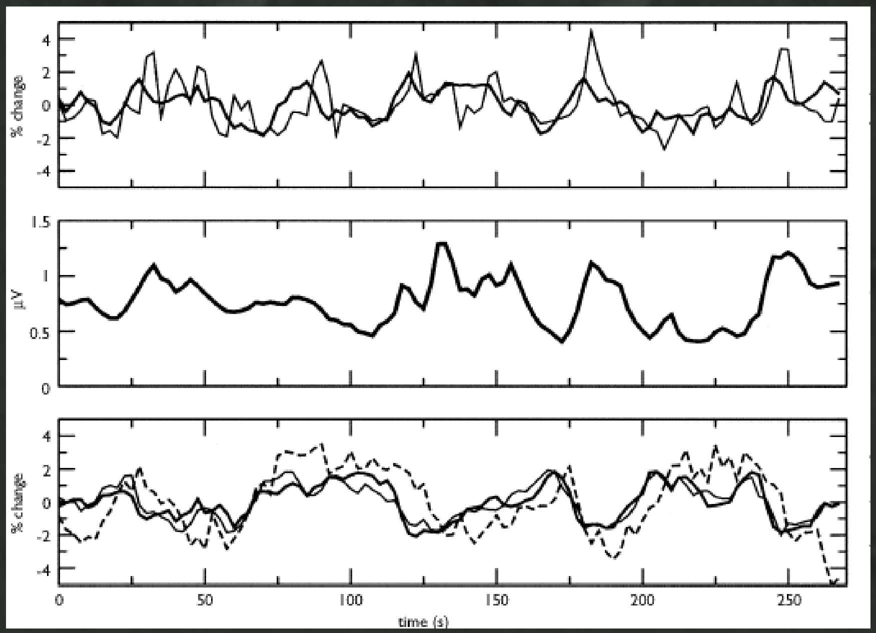
Paradigm Design

BOLD correlated with 10 Hz power during "Rest"

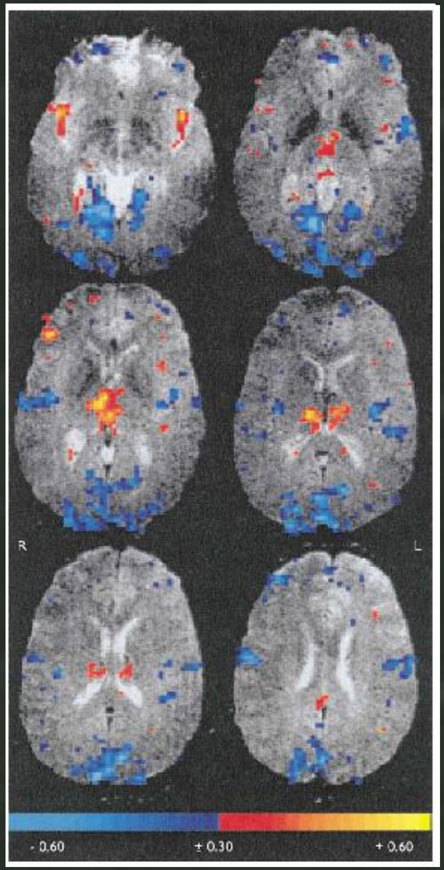
Positive

10 Hz power

Negative

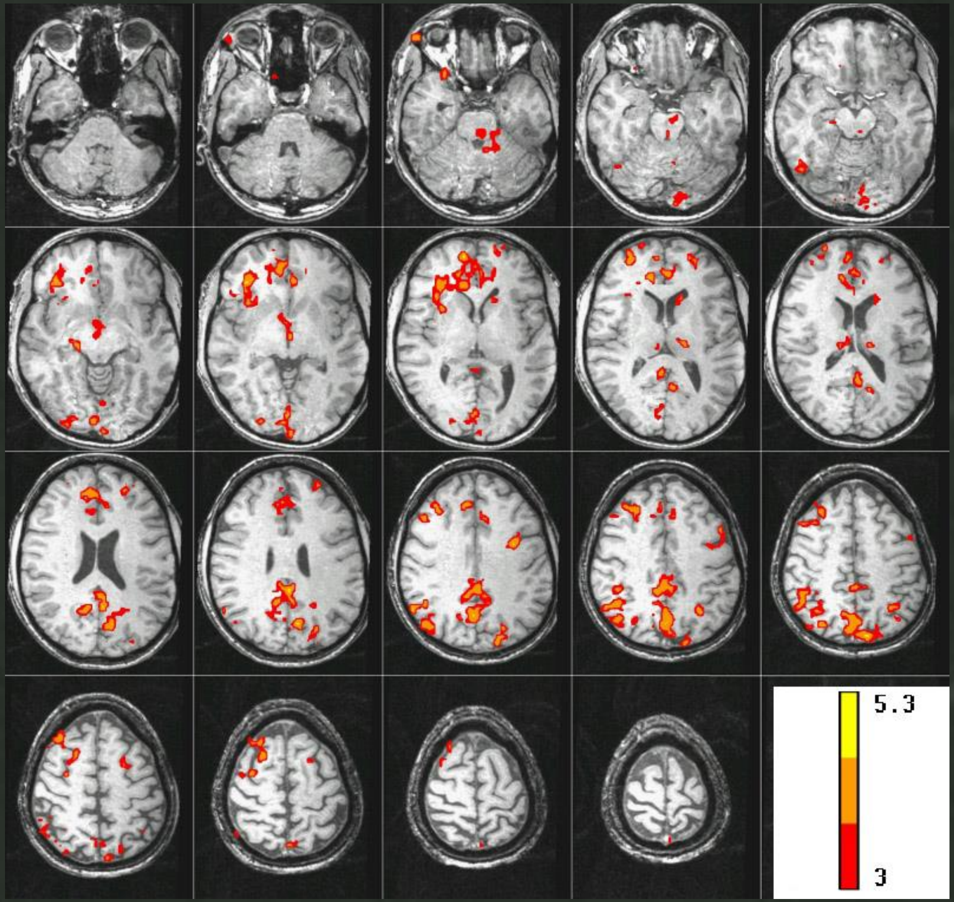


Goldman, et al (2002), Neuroreport



Paradigm Design

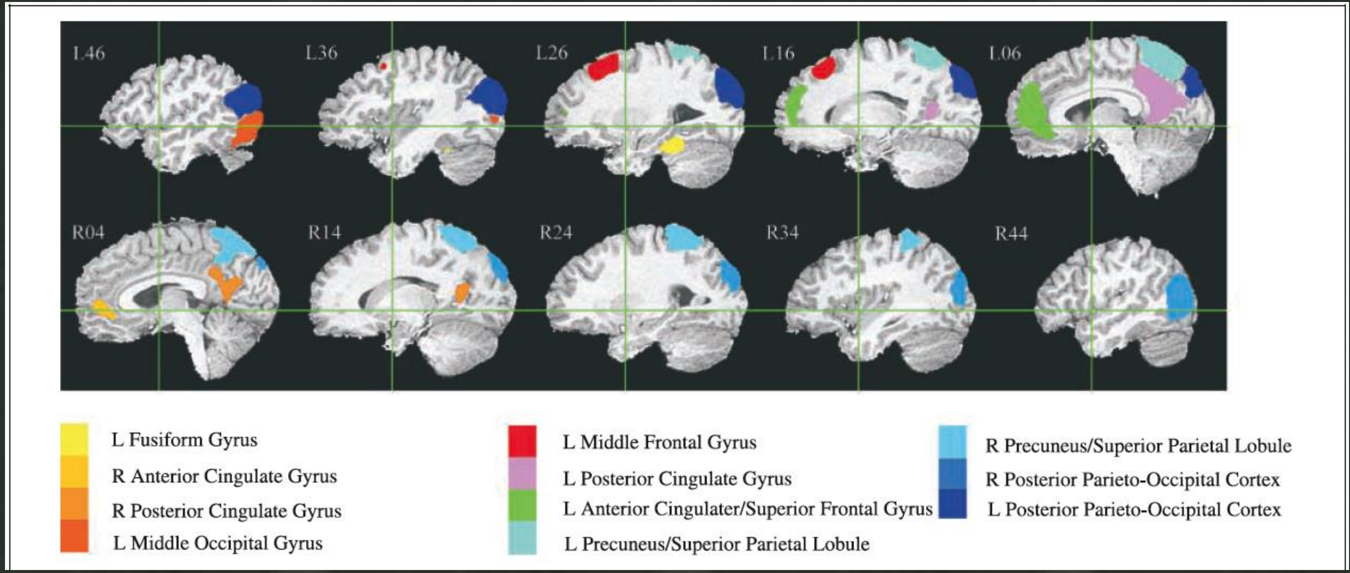
BOLD correlated with SCR during "Rest"

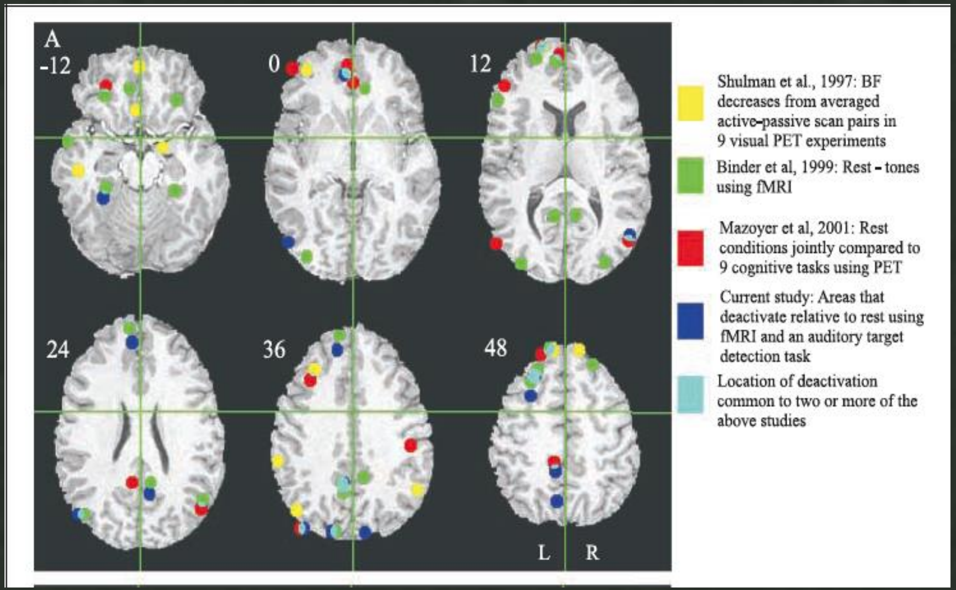


J. C. Patterson II, L. G. Ungerleider, and P. A Bandettini, *NeuroImage* ***17****: 1787-1806, (2002).*

Paradigm Design

Regions showing decreases during cognitive tasks

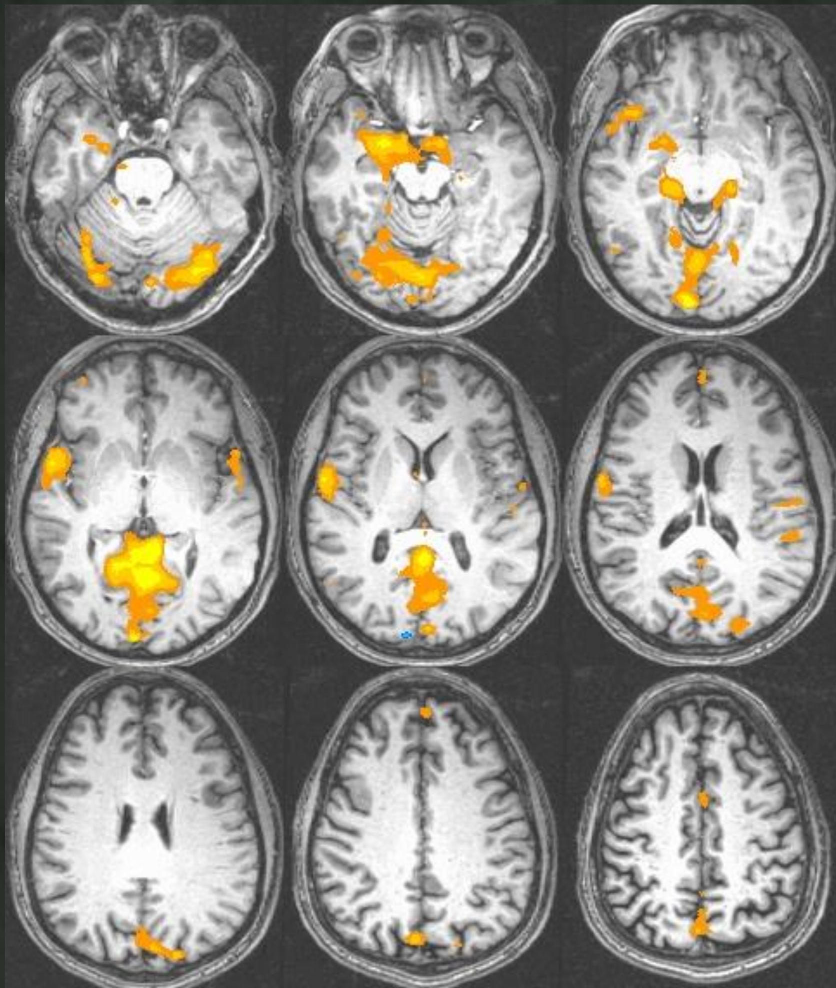




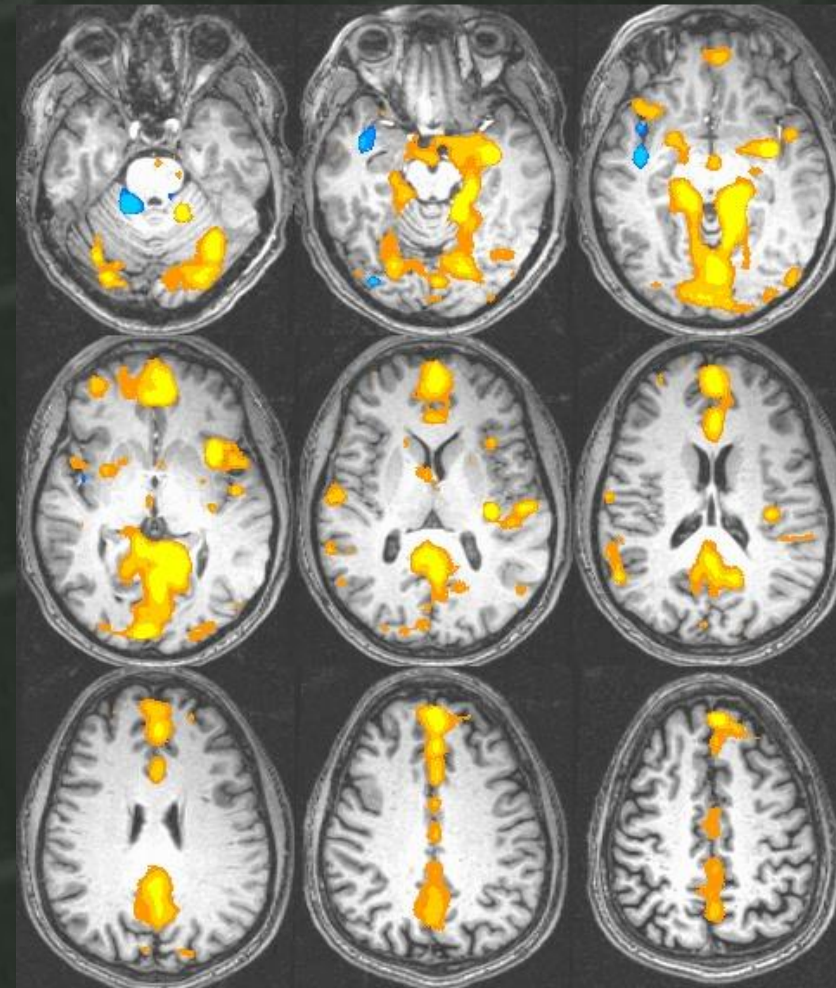
McKiernan, et al (2003), Journ. of Cog. Neurosci. 15 (3), 394-408

Paradigm Design

Right



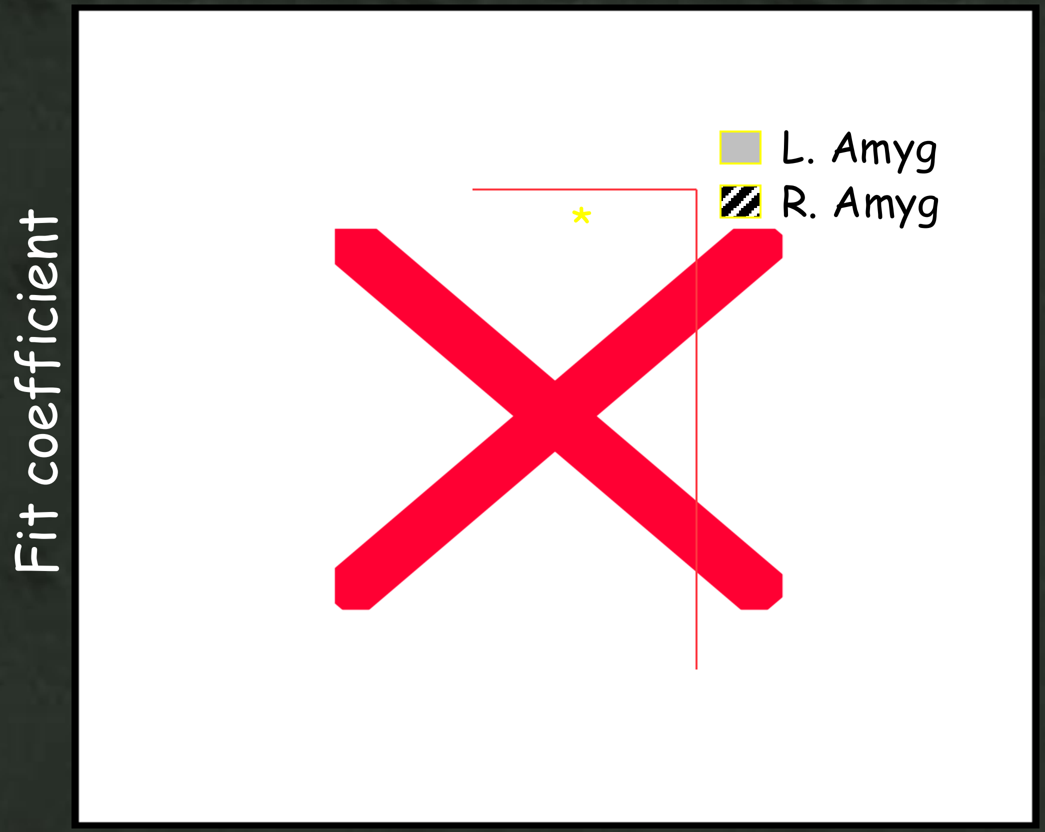
Left

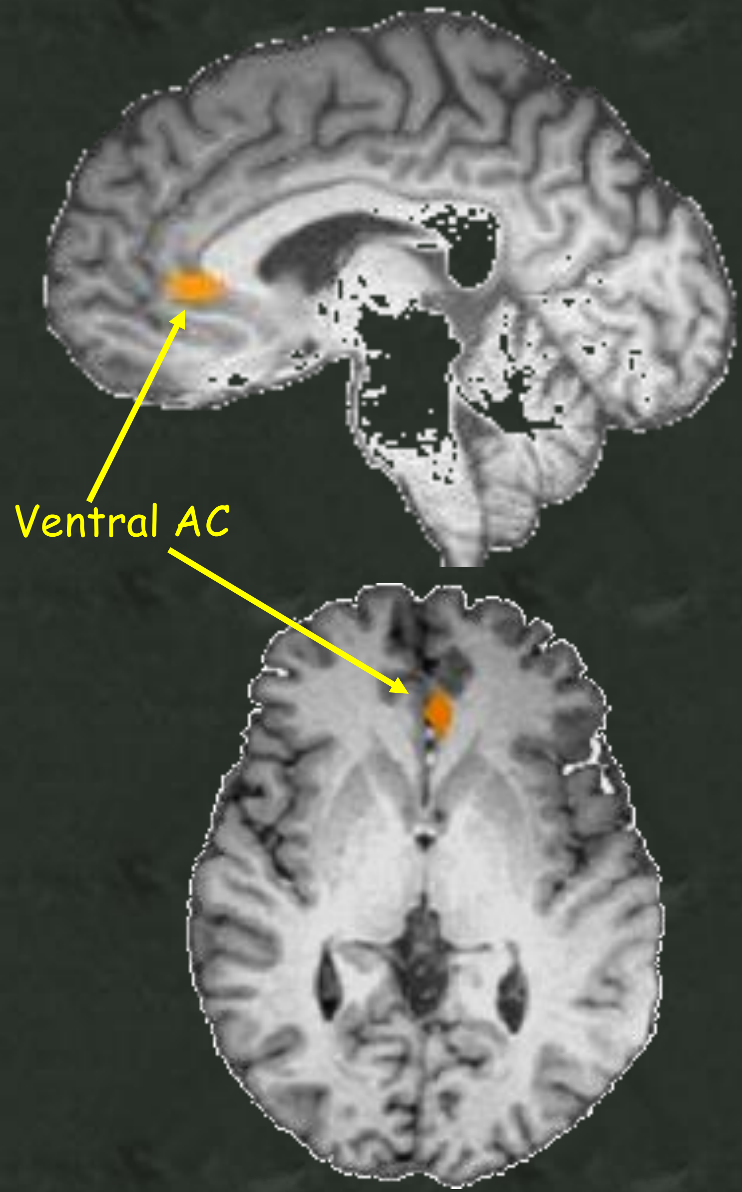


Brain regions showing strong correlation with left and right amygdala activity.

D. Knight, H. Nguyen

Paradigm Design



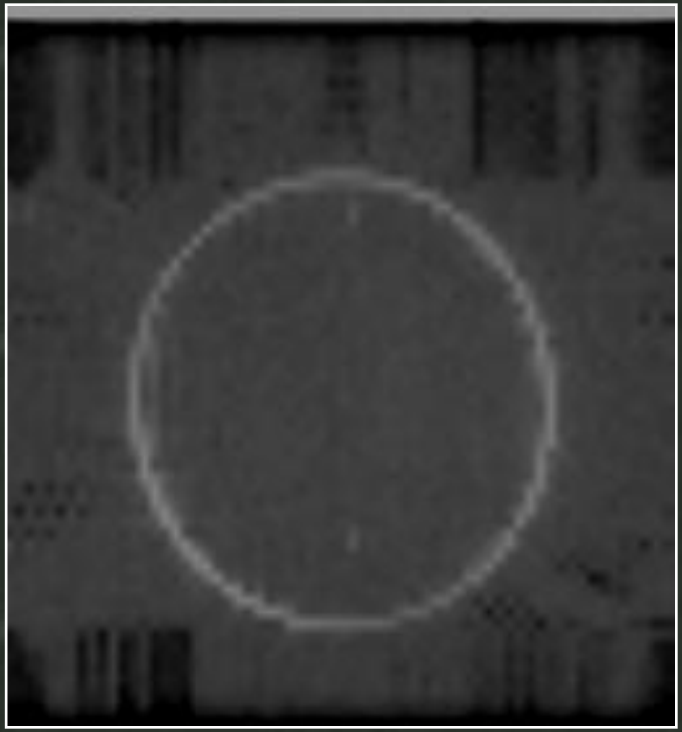


Fit coefficient comparing similarity of ventral AC activity with left and right amygdala activity. Activity within the ventral AC was more strongly associated with left than right amygdala activity.

D. Knight, H. Nguyen

Sensitivity and Noise

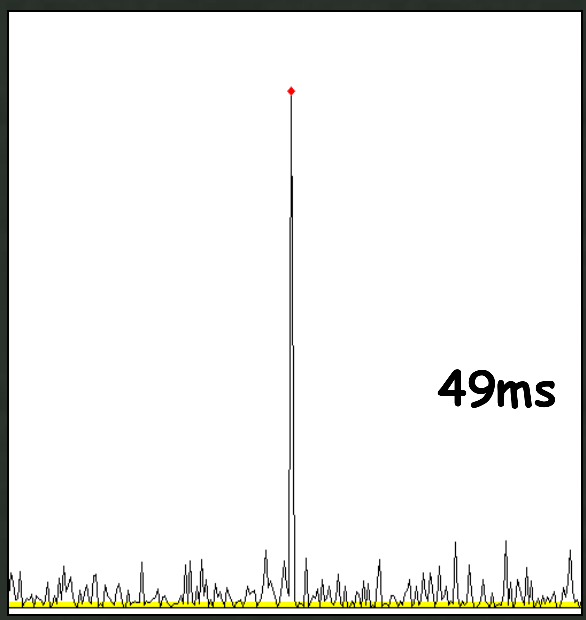
Phantom

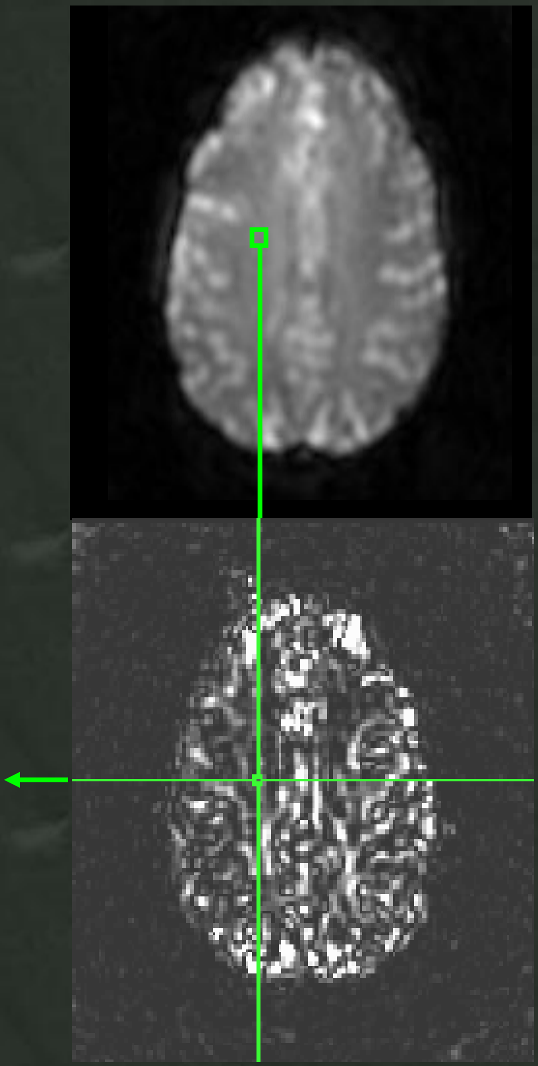


Brain

Sensitivity and Noise

Respiration Effects

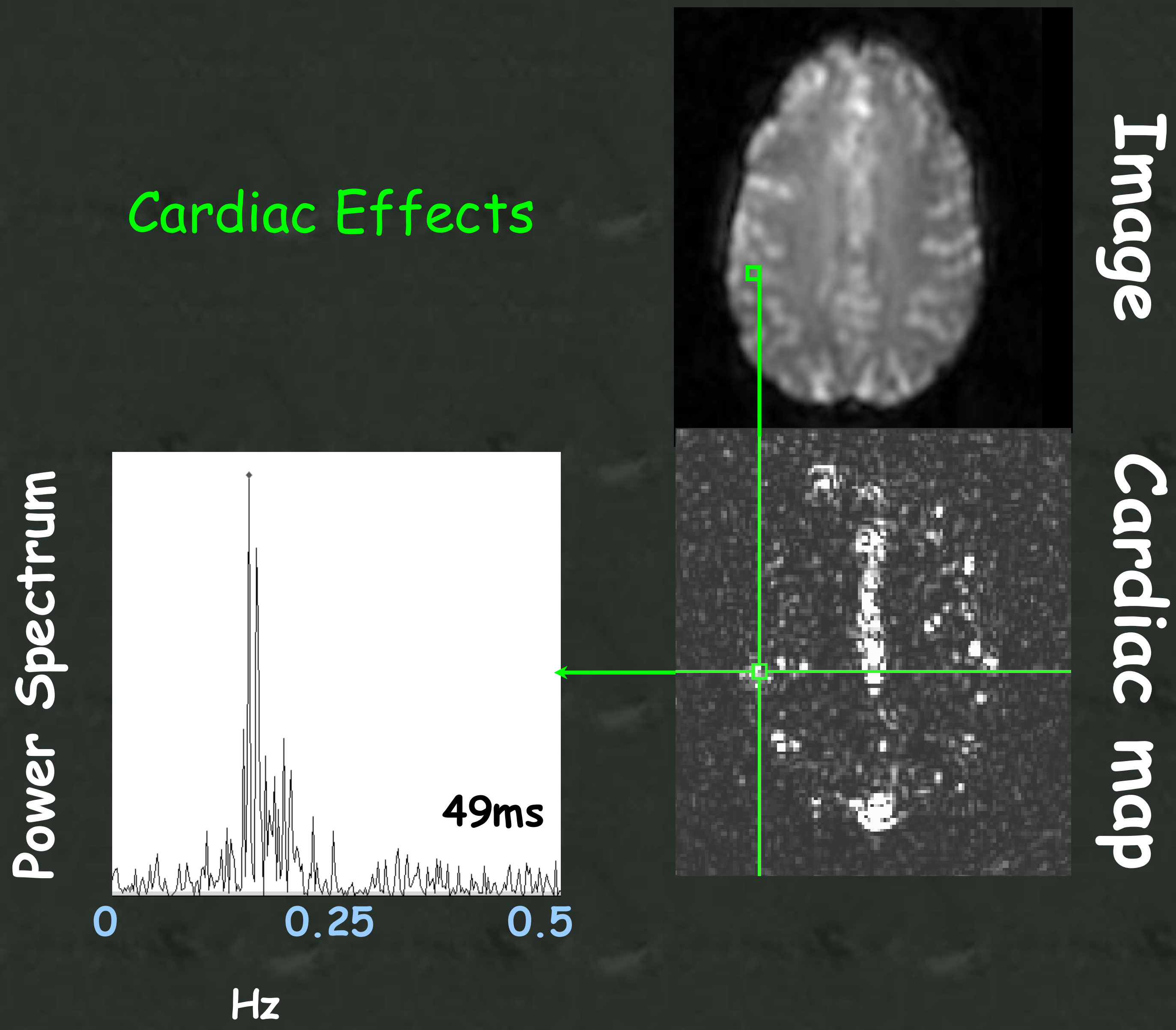




N. Petridou

Sensitivity and Noise

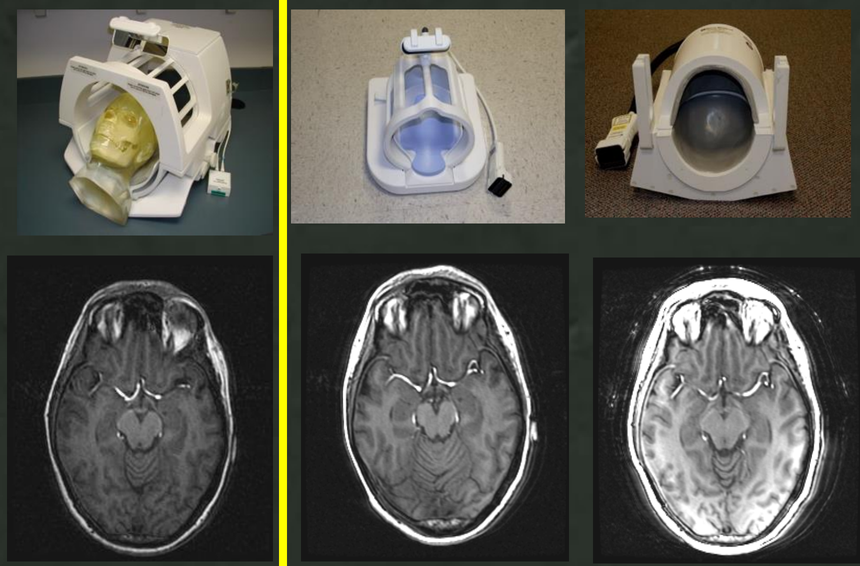
Cardiac Effects



N. Petridou

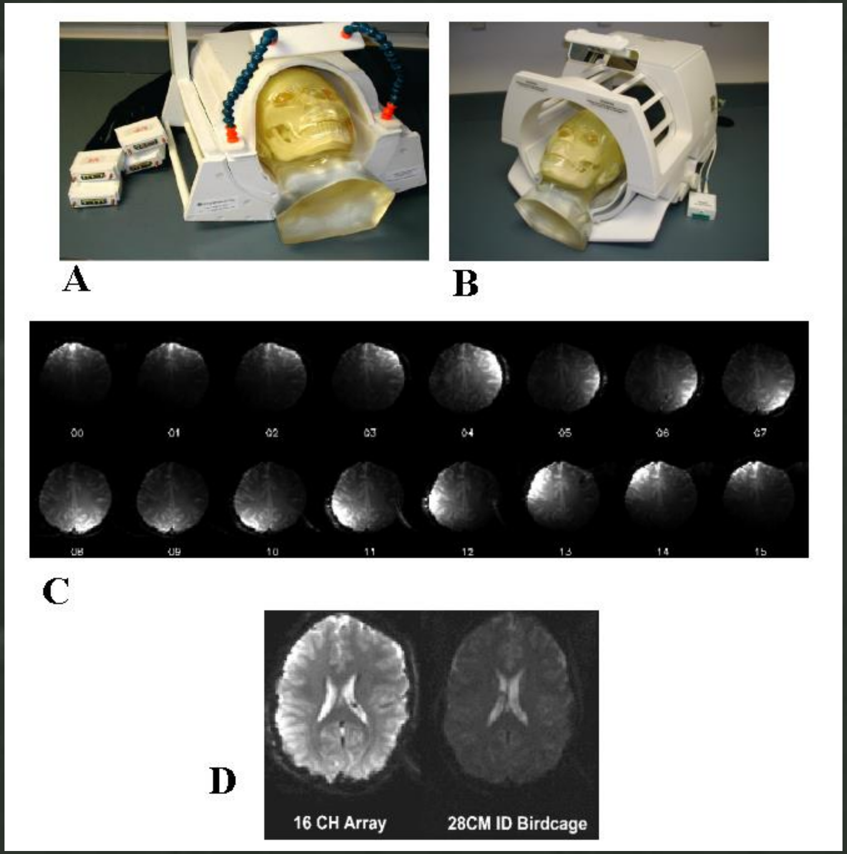
Sensitivity and Noise

8 channel parallel receiver coil



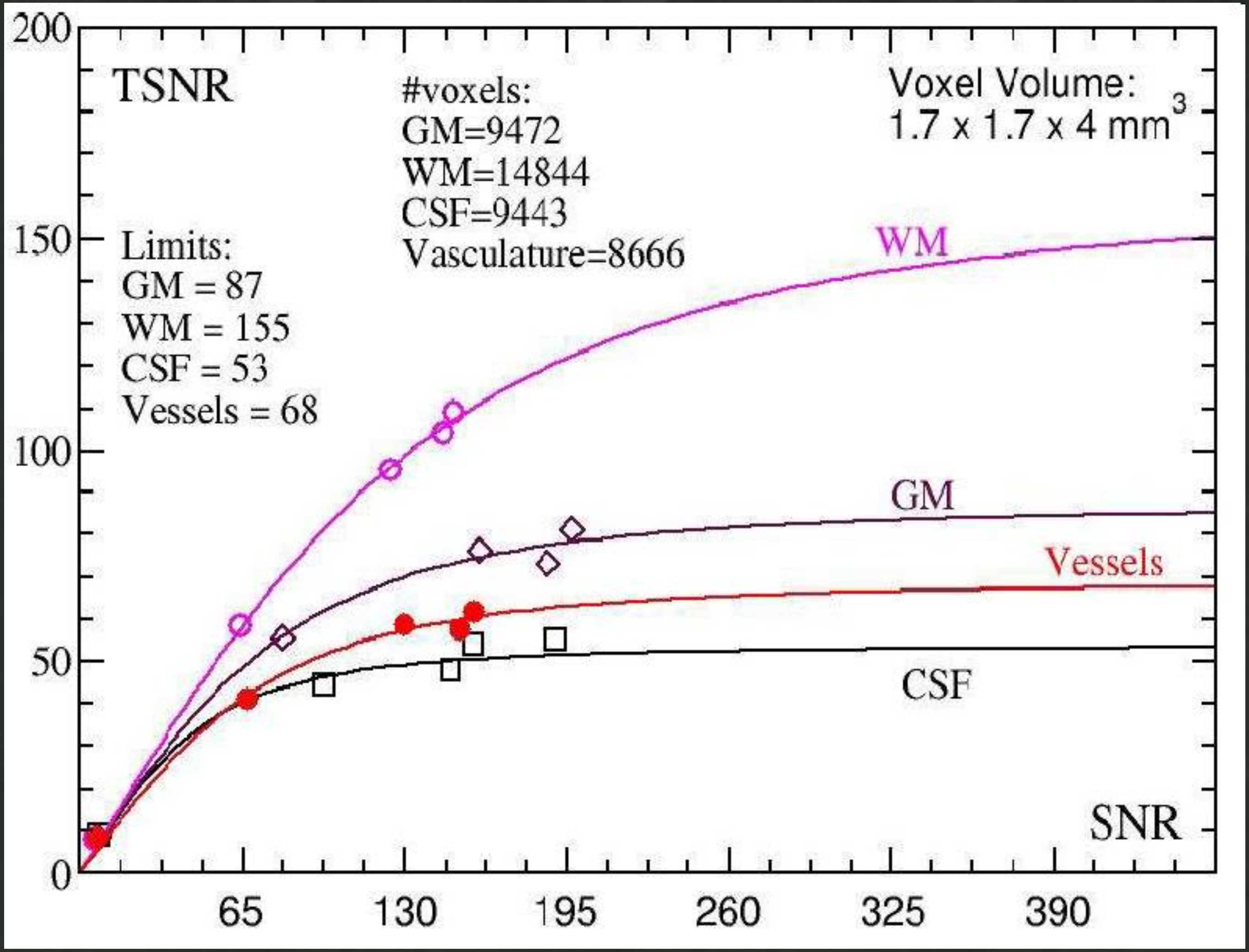
GE birdcage　　GE 8 channel coil　　Nova 8 channel coil

16 channel parallel receiver coil



J. Bodurka, et al, Magnetic Resonance in Medicine 51 (2004) 165-171.

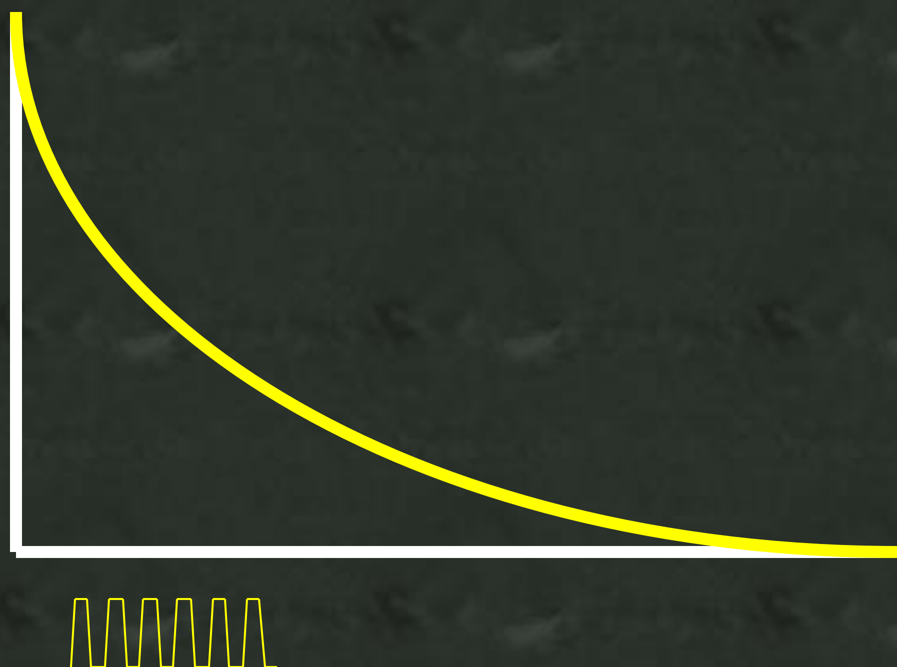
Sensitivity and Noise

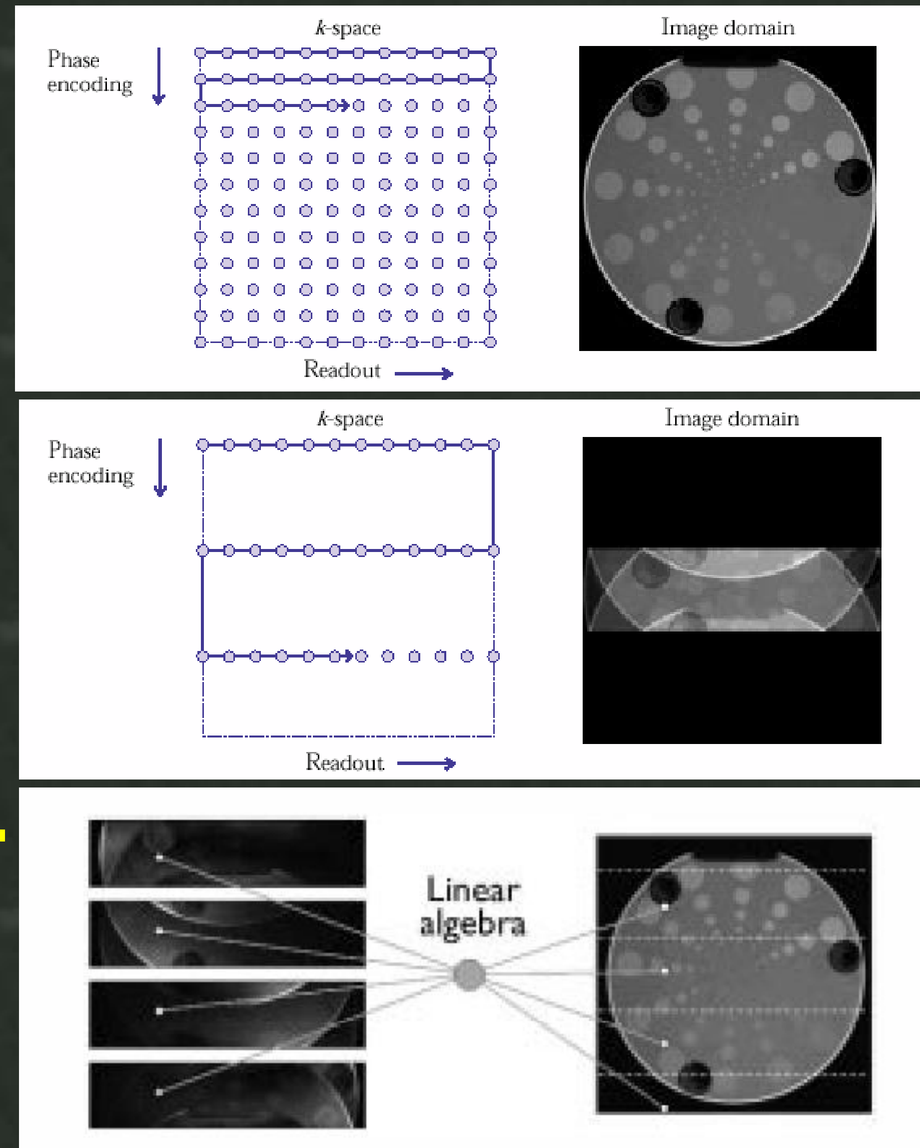


J. Bodurka

Sensitivity and Noise

SENSE Imaging



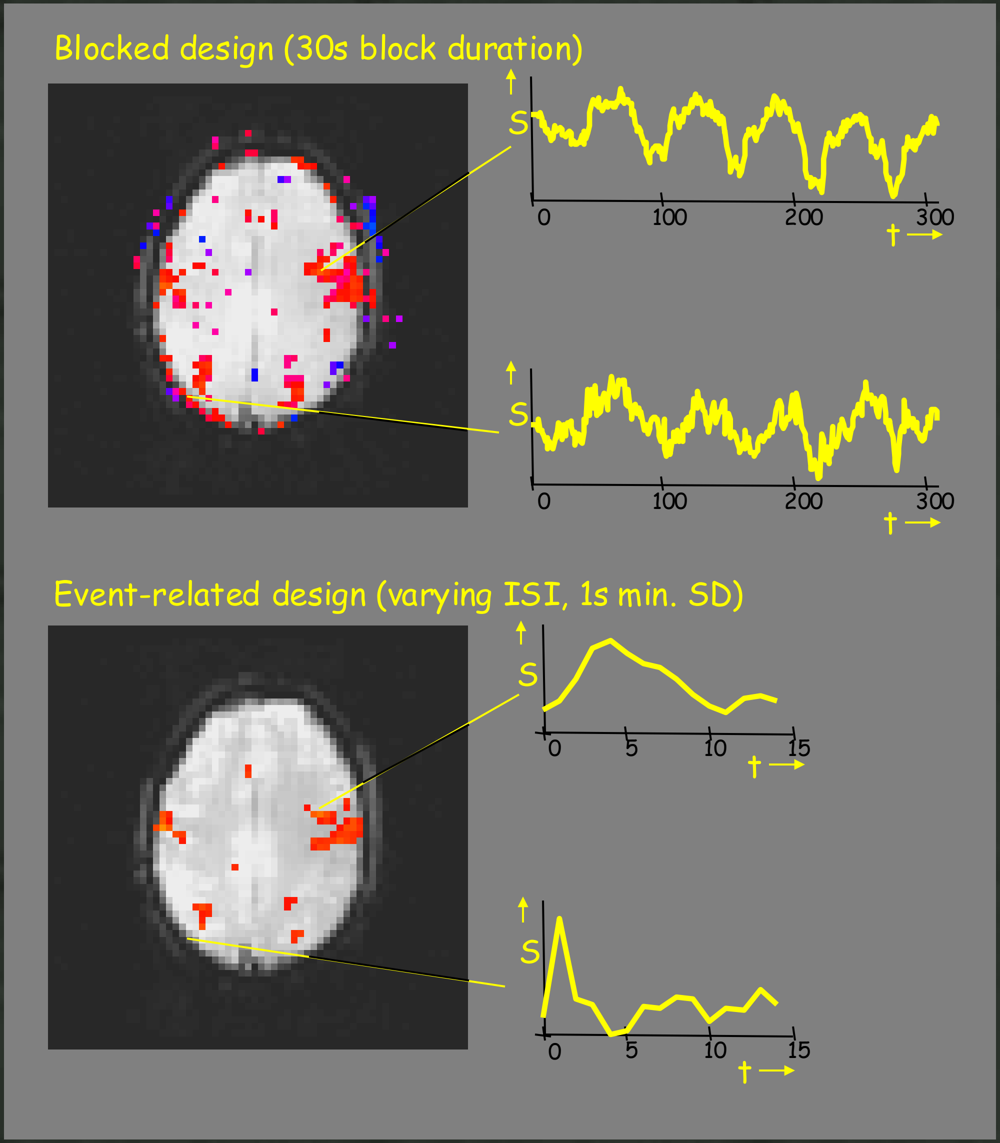


≈ 5 to 30 ms

Pruessmann, et al.

Sensitivity and Noise

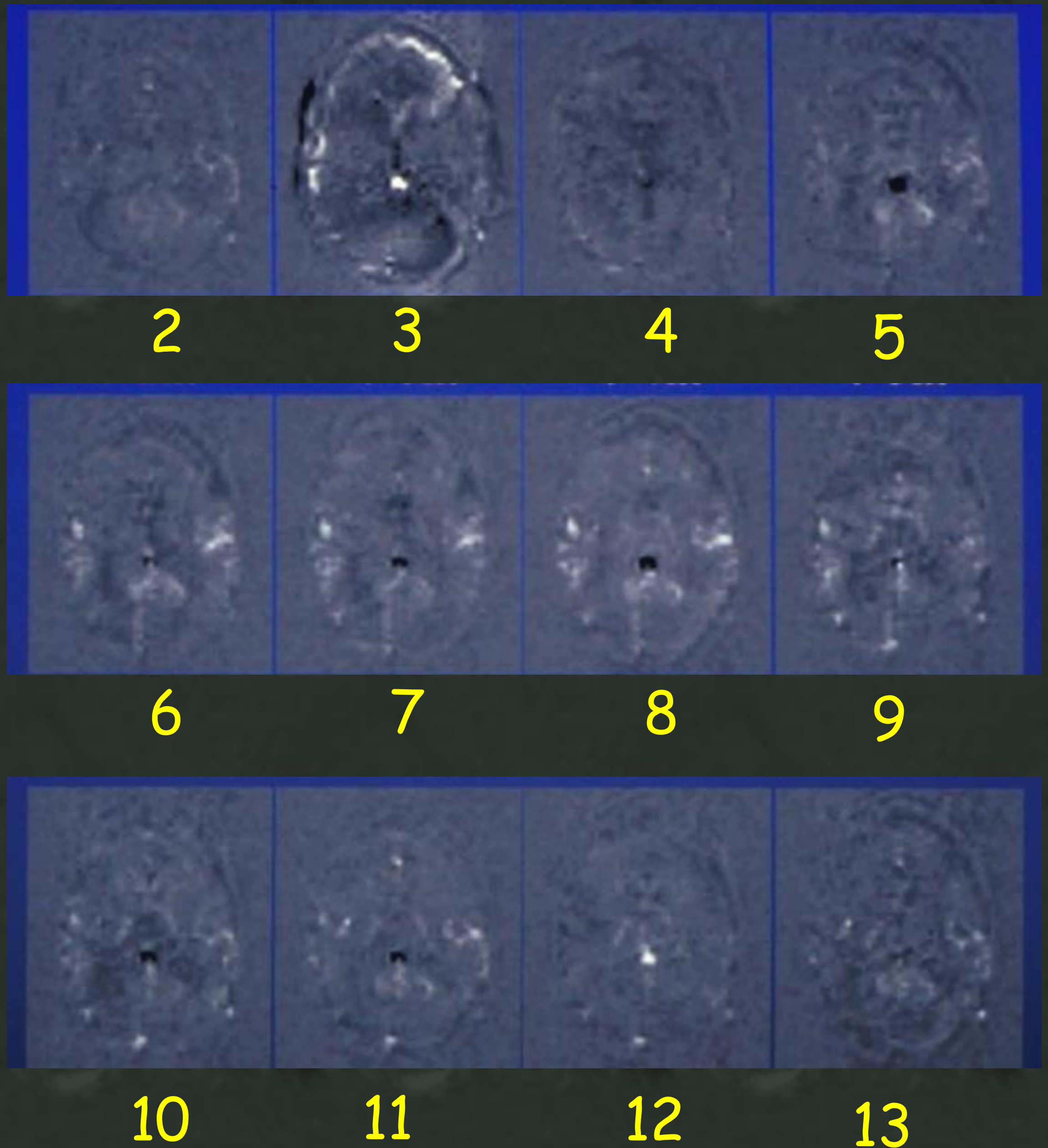
Stimulus Correlated Motion



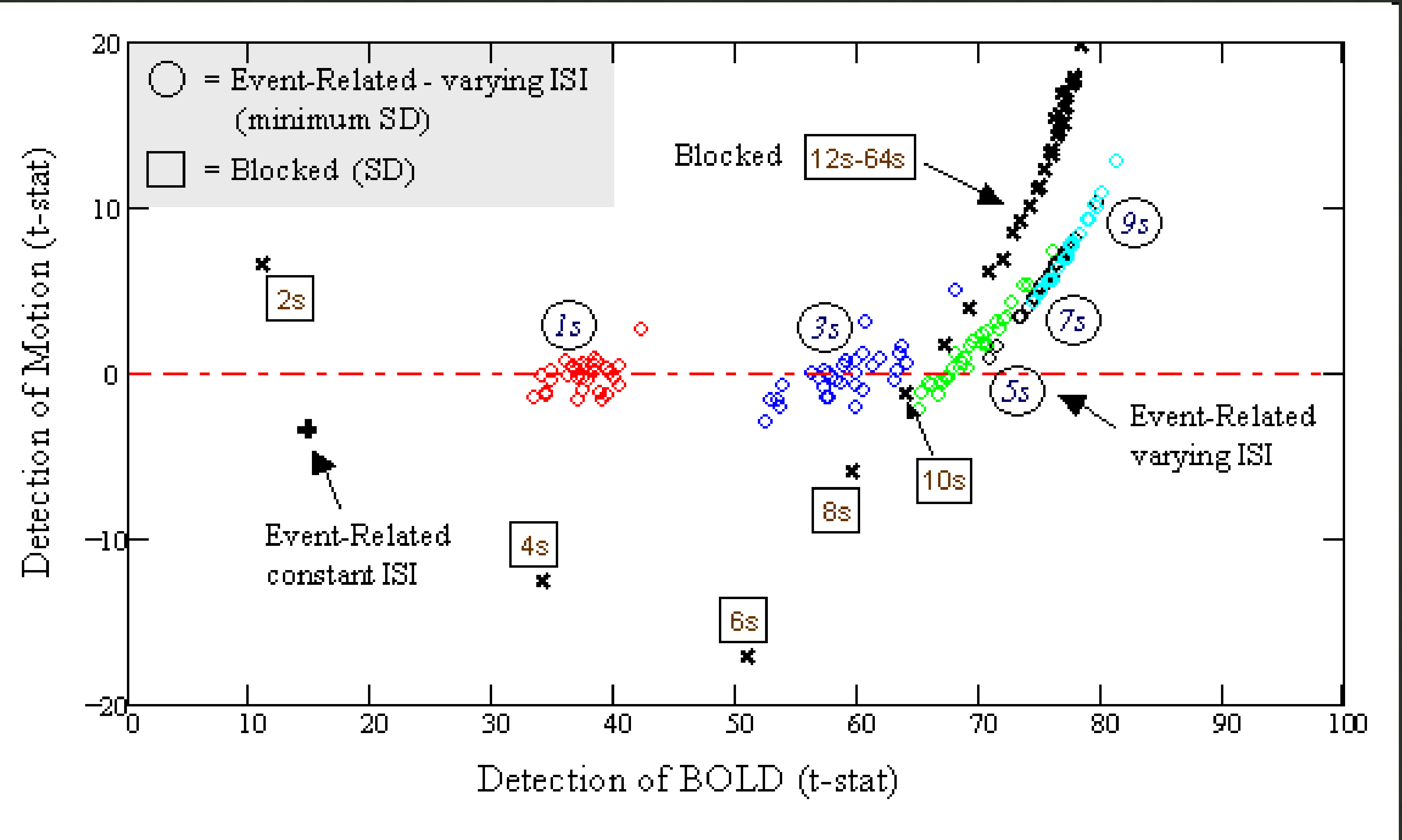
R. M. Birn, P. A. Bandettini, R. W. Cox, R. Shaker, Event - related fMRI of tasks involving brief motion. *Human Brain Mapping* **7: 106-114 (1999).**

Sensitivity and Noise

Overt Word Production



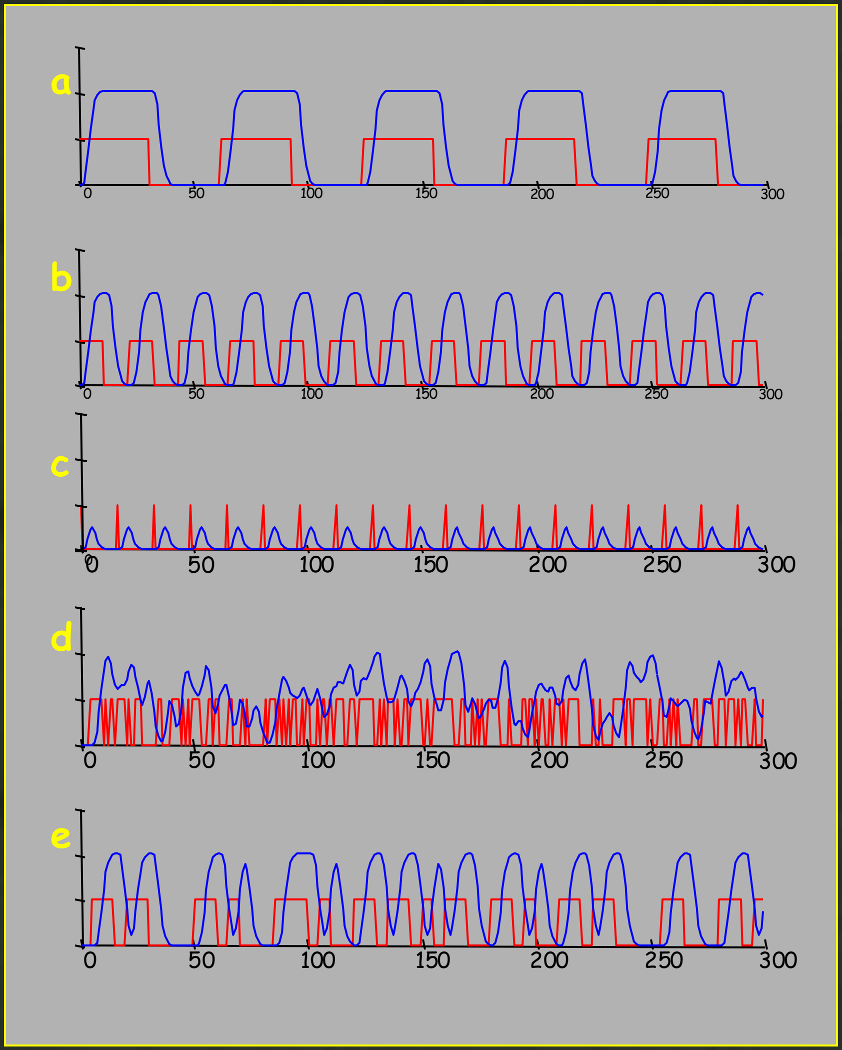
Sensitivity and Noise



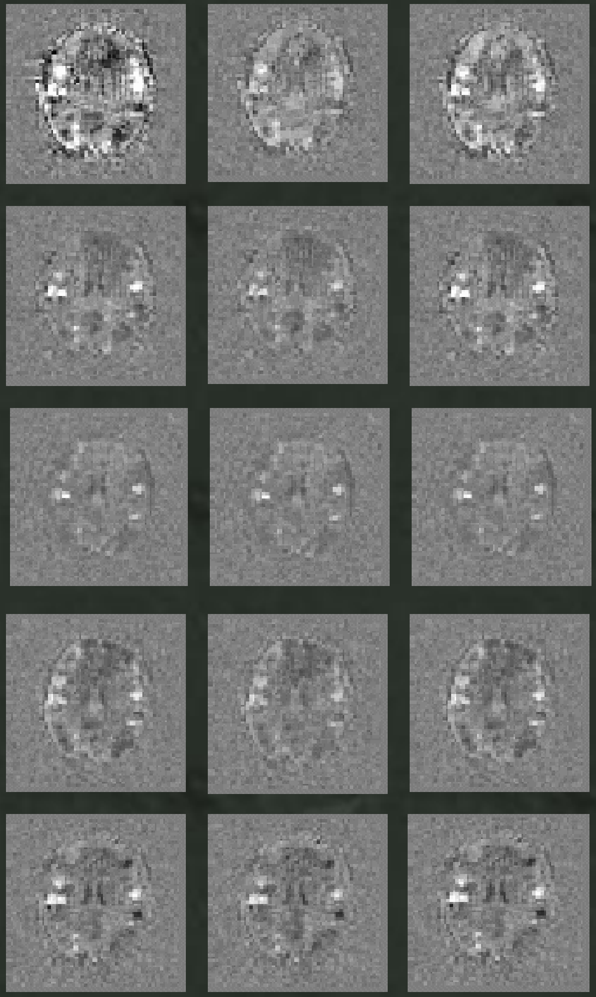
R.M. Birn, R. W. Cox, P. A. Bandettini. *NeuroImage*, **23 1046-1058 (2004)**

Sensitivity and Noise

Working around stimulus correlated motion



No correction | Ignore time pts during motion | Model motion



R.M. Birn, R. W. Cox, P. A. Bandettini. *NeuroImage*, **23 1046-1058 (2004)**

fMRI Contrast

Blood Volume
Blood Oxygenation
Perfusion
New Contrasts
The HRF: Spatial and Temporal Resolution
The HRF: Interpretation

fMRI Methodology

Paradigm Design
Sensitivity and Noise

Section on Functional Imaging Methods

Rasmus Birn
David Knight
Anthony Boemio
Nikolaus Kriegeskorte
Kevin Murphy
Monica Smith
Najah Waters
Marieke Mur
Natalia Petridou
Jason Diamond

Functional MRI Fa

Kay Kuhns
Sean Marrett
Wen-Ming Luh
Jerzy Bodurka
Adam Thomas
Jon West

Karen Bove-Bettis
Ellen Condon
Sahra Omar
Alda Ottley
Paula Rowser
Janet Ebron